MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

A CLOUD CLIMATOLOGY FOR KWAJALEIN

J.C. BARNES
H.K. BURKE
Group 35

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ABSTRACT

A cloud climatology for the Kwajalein area in the tropical Pacific presents cloud statistics for Kwajalein (9.4°N, 167.5°E) and 30 locations within approximately 1000 km of Kwajalein. The statistics are derived from a five-year sample (1977–1983) of the Air Force 3D-Nephanalysis Global Cloud Archive (known as the 3D-NEPH model). Mean cloud amounts and cloud amount frequencies of occurrence are presented for four representative months and for three cloud layers: low (surface to 1.9 km), middle (1.9 to 5.2 km), and high (>5.2 km). Cloud-top heights and temperatures are also estimated from atmospheric profile data. The cloud climatology presented in this report updates previous climatologies and presents cloud statistics for Kwajalein and the surrounding area in a format usable for determining LWIR upwelling earthshine.

ACKNOWLEDGMENTS

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The data tapes were processed and the display formats developed under the direction of Allan Patrick assisted by William DeCoste. Joyce Mulhern, Patricia Catalano, and Richard Bourbeau all assisted in the preparation of the report.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION AND SUMMARY

This report presents a cloud climatology for the Kwajalein area in the tropical Pacific. The cloud climatology is derived from the Air Force 3D-Nephanalysis (3D-NEPH) Global Cloud Archive. Atmospheric temperature and moisture profiles from the Air Force Summarized Analysis Data Set (SADS) are used to derive estimates of cloud-top heights and temperatures. The understanding of long-wave infrared (LWIR) earthshine is a key element for the data analysis of missile systems reentering the atmosphere. To establish upwelling LWIR earthshine in the Kwajalein area, a vital area for many test programs, total cloud amount, cloud-top heights, and temperatures must be known.

The cloud climatology statistics are presented for 30 locations centered at Kwajalein (9.4°N, 167.5°E), representing an area of approximately 1000-km radius (0 to 20°N, 155°E to 180°). The study is based on a five-year sample period (1977 to 1983). Although more recent cloud archive data have been collected by the Air Force, the earlier 3D-NEPH sample period was selected for this study because those data were available in a readily usable, summarized format.

Climatological studies of Pacific Ocean cloudiness have been carried out previously using various data sources, including early satellite observations and ship reports. Some studies of cloud cover over the island of Kwajalein are also available, but these studies have usually been from fairly limited data samples. The objective of this study was to update the previous cloud climatologies and to provide cloud statistics not only for Kwajalein but for the surrounding area in a format usable for determining LWIR upwelling earthshine.

Although it is difficult to compare this cloud climatology directly with the previous climatologies because of the different data sources and different methods used to categorize cloud types and layers, the statistics are consistent overall with other data sources and with climatological considerations. These statistics show that there is much less cloud cover to the north of Kwajalein and greater amounts to the south in all seasons. Although the seasonal variation in cloud amount is relatively small, the statistics for the locations at 10°and for Kwajalein (9.4°N) indicate January to be the least cloudy month, and July and October to be the most cloudy; this seasonal trend is in agreement with other data sources for Kwajalein, which show January and February as the least cloudy months. Imagery from the Japanese Geosynchronous Meteorological Satellite (GMS), which covers the western Pacific Ocean, is also consistent over the year with the statistical analysis carried out here. Nevertheless, some discrepancies appear among the different climatologies with certain limitations to each data source. The main limitations in the 3D-NEPH data base appear to be the detection of high cirrus cloud; the occurrence of cirrus in the area around Kwajalein may be as much as 20% greater than the amount indicated in the statistics derived from satellite data alone. Cirrus cloud statistics derived from satellite data are inadequate. The occurrence of high cirrus may compromise LWIR data collection from aircraft platforms; however, cirrus poses less of a problem on the estimation of LWIR upwelling earthshine computations.

The data source, format, and processing are described in Section 2 of this report. A discussion of the climate of the Kwajalein area, including sample satellite images showing typical cloud patterns, is given in Section 3; the results of other cloud studies of the tropical Pacific, including studies of the occurrence of high cirrus clouds, are also discussed in that section. The cloud climatology statistics derived for the Kwajalein area are discussed in Section 4, which includes a comparison with cloud

statistics derived in other studies and a description of on-going cloud data collection projects. The atmospheric temperature and moisture profile data are given in Section 5, and the estimates of cloud-top heights and temperatures are in Section 6. The mean cloud amount, cloud amount frequency of occurrence, and atmospheric profile statistics for the various locations centered at Kwajalein are presented in Appendices A, B, and C, respectively.

2. SOURCE OF DATA

2.1 CLOUD DATA SET

2.1.1 Description of the 3D-NEPH Data Set

The Kwajalein cloud climatology is based on the Air Force 3D-NEPH archive, which is an archive of cloud data derived primarily from satellite observations with input from other Air Force data sets. The archive was originally referred to as the 3D-NEPH model, but since late 1983 it has been called the RT-NEPH model. The 3D-NEPH model is described in detail by Fye [1]. A similar data set was used in an earlier study [2] of a cloud climatology for the North Pacific area centered at Shemya, Alaska. The 3D-NEPH data set for Kwajalein is for the sample period 1977 to 1983.

Use of the more recent RT-NEPH data set was considered. The RT-NEPH data set is available from 1984 to the present and is an improved model that provides a much finer breakdown of cloud layers than does the 3D-NEPH model (254 cloud layers versus 15 layers). The difficulty in using the newer data set is that the RT-NEPH data are not yet available in summarized form. It would have taken a major effort and several months to summarize the data into a format suitable for compiling a cloud climatology. Moreover, for the purposes of this study, the RT-NEPH model would have provided an overwhelming amount of data, and the finer breakdown of cloud layers would not have provided much additional useful cloud information. Therefore, it was decided to use the original 3D-NEPH summarized data set.

2.1.2 Data Format

The cloud data set was acquired on tape from the Air Force Environmental Technical Applications Center (ETAC) in the form of monthly mean values of cloud amount and frequency of occurrence. The data were acquired for 30 grid-point locations (at $5° \times 5°$ intervals) from 0 to 20°N and 155°E to 180°, covering an area within approximately 1000 km of Kwajalein; data were also acquired for Kwajalein itself (9.4°N, 167.5°E). In the 3D-NEPH data set, the cloud amounts are given twice per day (noon and midnight) at 5% increments from zero (no cloud) to 100% (completely cloudy).

The initial data set was broken down into three cloud layers: low, middle, and high clouds. Subsequently, an additional data set was acquired to provide a finer breakdown of the middle- and high-cloud layers. This data set provided six additional layers that overlap somewhat with the middle- and high-cloud layers of the original data set. The heights of the cloud layers are given in Table 1.

2.1.3 Processing of Cloud Data

The mean cloud percent and cloud amount frequency of occurrence were plotted in graphical format for four representative months: January, April, July, and October. The cloud amount frequency of occurrence was broken down into five categories: 0% (clear sky), 5 to 35%, 40 to 65%, 70 to 95%, and 100% (overcast sky). The additional six-cloud layer data set was processed and plotted separately from the original three-cloud layer data set.

TABLE 1
3D-NEPH Cloud Layers

Initial Data Set	
Low cloud:	Surface to 6,000 ft (surface to 1,900 m)
Middle cloud:	6,000 to 18,000 ft (1,900 to 5,200 m)
High cloud:	Above 18,000 ft (above 5,200 m)
Additional Data Set	
10,000 – 14,000 ft	(3,048 – 4,267 m)
14,000 – 18,000 ft	(4,267 – 5,486 m)
18,000 – 22,000 ft	(5,486 – 6,706 m)
22,000 – 26,000 ft	(6,706 – 7,925 m)
26,000 – 35,000 ft	(7,925 – 10,668 m)
35,000 – 55,000 ft	(10,668 – 16,764 m)

2.2 ATMOSPHERIC PROFILE DATA SET

Atmospheric profiles of temperature and moisture from the Air Force Summarized Analysis Data Set (SADS) were also acquired from the Air Force ETAC for approximately the same sample period as for the cloud data (1977 to 1982). The temperature profiles are from the surface to the 10-mb level (about 30 km), and the moisture profiles are from the surface to the 300-mb level (about 9 km). The temperature and moisture profiles were plotted for the same 5° × 5° grid-point locations and representative months as for the cloud data, except for two locations in the southeast corner of the study area (0°, 175°E and 0°, 180°), which were missing from the atmospheric profile data set.

In this particular data set, the moisture values were given in absolute humidity (gm/m^3). For the purposes of cloud studies, moisture values in terms of dew-point depression (the difference between temperature and dew point) are more useful because dew-point depression can be related to the likelihood of cloud development (see Section 3). The moisture profiles were converted, therefore, from absolute humidity to dew point (and then to dew-point depression) using Teten's formula [3]. The conversion process results in some error, especially at low temperatures, but the accuracy of the resulting profiles is adequate for general climatological purposes, such as in this study.

2.3 SATELLITE IMAGERY

The Japanese Geosynchronous Meteorological Satellite (GMS) covers the entire western Pacific Ocean. These images are available on a daily basis in facsimile format. The GMS full-disk images are at a degraded resolution, but they are useful for assessing the overall cloudiness of the tropical Pacific

and, therefore, are useful for checking the consistency of the derived cloud statistics. The IR images also provide some information on cloud height through a shaded gray-tone scale.

In addition to the full-disk facsimile images, a few full-resolution GMS enlarged prints and NOAA satellite prints were acquired for the Kwajalein area. These images, in the visible and IR bands, provide examples in greater detail of cloud patterns around Kwajalein. The characteristics of the NOAA polar-orbiting satellites are quite similar to those of the Air Force Defense Meteorological Satellite Program (DMSP) satellites, which are the main input to the 3D-NEPH cloud archive.

3. BACKGROUND DISCUSSION OF KWAJALEIN AREA CLOUD CLIMATOLOGY

3.1 DESCRIPTION OF KWAJALEIN CLIMATE

The Kwajalein Atoll, one of the largest coral atolls in the world, is part of the Marshall Island group located in the western Pacific Ocean (see Figure 1). The coordinates of Kwajalein used in this study (9.4°N, 167.5°E) are the coordinates of Roi Namur at the northern tip of the atoll; Kwajalein Island is located near the southernmost part of the atoll at 8.7°N. The land surfaces of the islands comprising the atoll are at low elevation (only a few feet above sea level) and have very little effect on the climate of the locality.

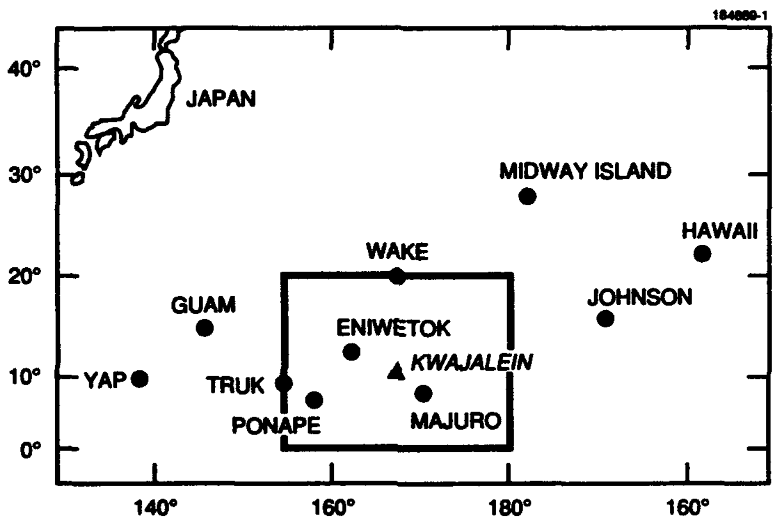

Figure 1. Map of the tropical Pacific Ocean. The area around Kwajalein within which the cloud climatology statistics were derived is outlined.

Climatologically, Kwajalein is located in the belt of trade winds that blow from the northeast toward the southwest. According to the description in the Local Climatological Data (LCD) [4],

> ... Kwajalein has a tropical marine climate that is characterized by a relatively high annual rainfall and warm to hot, humid weather throughout the year. The principal rainfall season is May through November, with almost constant cloudiness and frequent moderate to heavy showers. The dry season is December through April, with lighter showers of shorter duration; cloudiness is at a minimum and the sky is less than one-half covered most of the time, but clear skies are rare. The northeast trade winds are stronger during the dry season.

It should be noted that despite the above description of the Kwajalein climate, the 30-year mean sky cover given in the LCD does not vary much from month to month, ranging from 76% in February to 85%

in July and October. The mean number of days with precipitation ranges from a low of 13 days in February to a high of 23 days in each month from June through November. The average sky cover for the year of 1986 ranges from a low of 75% in January to a high of 98% in April, June, and December; no significant difference is observed in the 1986 average sky cover from sunrise to sunset and from midnight to midnight.

In a publication describing the climate of the North Pacific Ocean [5], the statistics are much the same with the mean monthly cloud amount ranging from 71 to 86%, and the number of days with precipitation ranging from a low of 14 in February to a high of 24 in July, August, and November. For comparison, the islands of Yap, Truk, Majuro, and Ponape (all between 7°and 9°; see Figure 1) all have greater mean cloud amounts than Kwajalein, whereas Eniwetok (11°N) has less cloud. In this report, clouds in the tropics are often organized into groups called "cloud clusters," the horizontal dimensions of which range from 2° to 12° longitude; these clusters may be as large as 5×10^5 km^2 in the Kwajalein area. The low-level cloud band north of the equator, where these clusters are found, varies in intensity with season. West of Kwajalein, the cloud clusters may form well-developed vortices that become typhoons; in the central Pacific, vortices rarely develop and typhoons are essentially nonexistent.

Differences in cloud cover in the Kwajalein area may be associated with longitudinal differences in the wind regimes; during the summer, stronger northeast trade winds occur to the east of Kwajalein, whereas southerly winds from the equator may occur in the area west of Kwajalein. According to Terada and Hanzawa [5], the northeast trades blow in a layer from the surface to 8 to 10 km with the air being moist below 2 km and dry above 2 km. The air temperature at Kwajalein is near 28°C all year with very little difference between the air and sea surface temperatures.

Three examples of GMS full-disk satellite images showing cloud cover in the western Pacific are given in Figures 2(a), (b), and (c). In these IR images, the lower (warmer) clouds appear in darker tones and the higher (colder) clouds in lighter tones. The location of Kwajalein is indicated in each image, and the approximate area for which cloud statistics were derived (0° to 20°N, 155°E to 180°) is outlined. The 29 May image [Figure 2(a)] shows cloud areas to the east and west of Kwajalein, but it shows an essentially cloud-free area to the north; the 11 July image [Figure 2(b)] shows extensive cloud cover south and east of Kwajalein with few clouds to the north and west; the 14 August image [Figure 2(c)] shows a very active cloud pattern with a major cloud mass northwest of Kwajalein.

Two examples of GMS full-resolution IR prints of the Kwajalein area are shown in Figures 3(a) and (b). The location of Kwajalein and the area used in the study are indicated. The 29 May image [Figure 3(a)] shows Kwajalein near the boundary of a cloud area to the southeast (area of bright tone with cold, high clouds likely). This image is five hours later than the facsimile image shown in Figure 2(a); note the greater cloud detail in Figure 3(a). The 5 June image [Figure 3(b)] shows an extremely active cloud pattern covering the entire Kwajalein area; this pattern is indicative of an extremely moist tropical atmosphere with clouds at all levels.

An analysis of the Kwajalein Environmental Severity Index (ESI) — the vertically integrated quantity of water mass weighted as a function of height — was carried out by Bussey [6]. This analysis, which provides an assessment of liquid-water content (LWC) derived from upper-air observations, surface observations, and satellite images, was carried out up to the tropopause, which, in the Kwajalein area, occurs at the 16- to 17-km level. The tropopause, denoted by a significant change in the thermal lapse rate (from decreasing with height to stable or increasing), is an important feature in tropical cloud climatology because

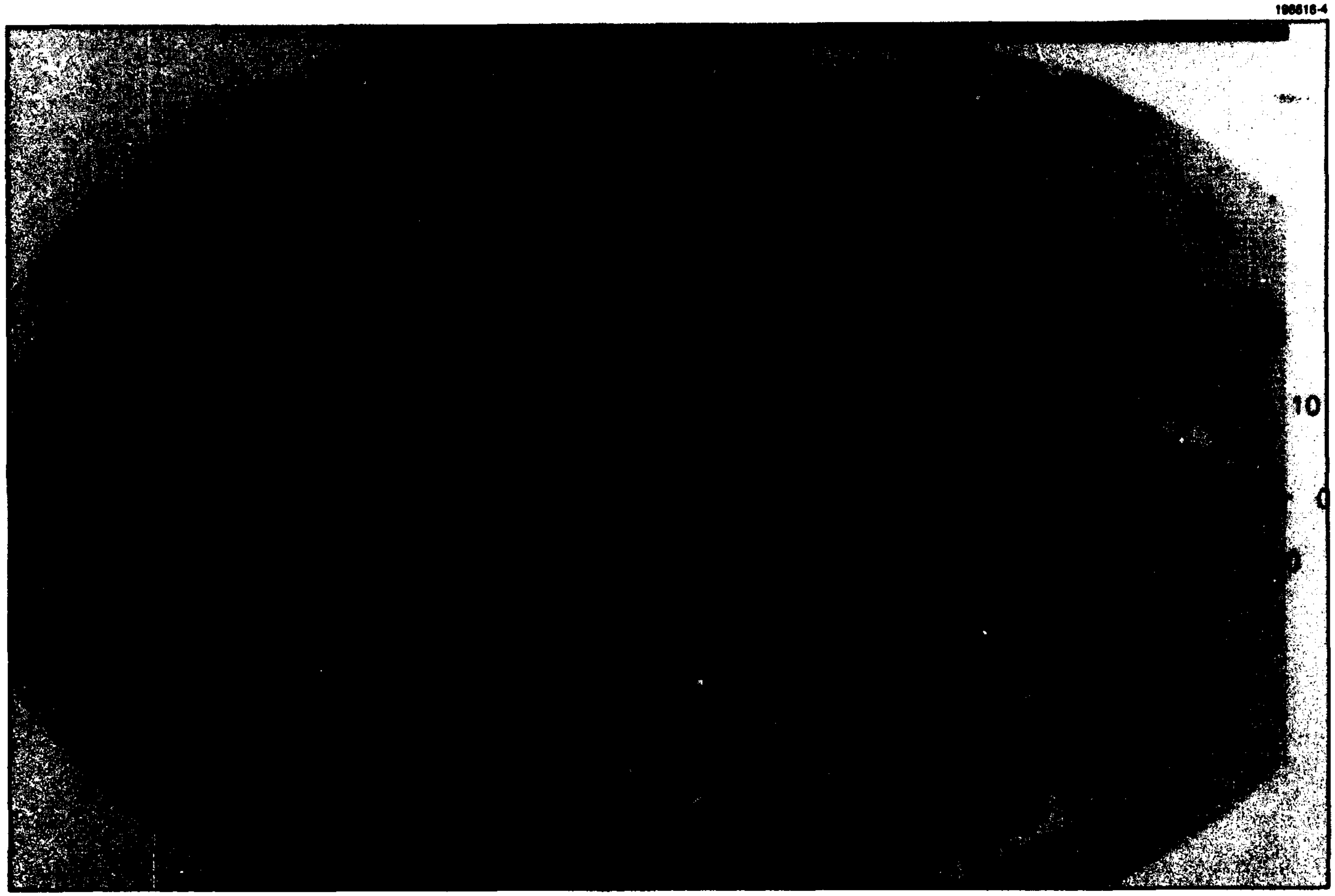

Figure 2(a). GMS IR full-disk facsimile image covering the western Pacific Ocean on 29 May 1991. Kwajalein is indicated at K; the area for which cloud statistics were derived is outlined.

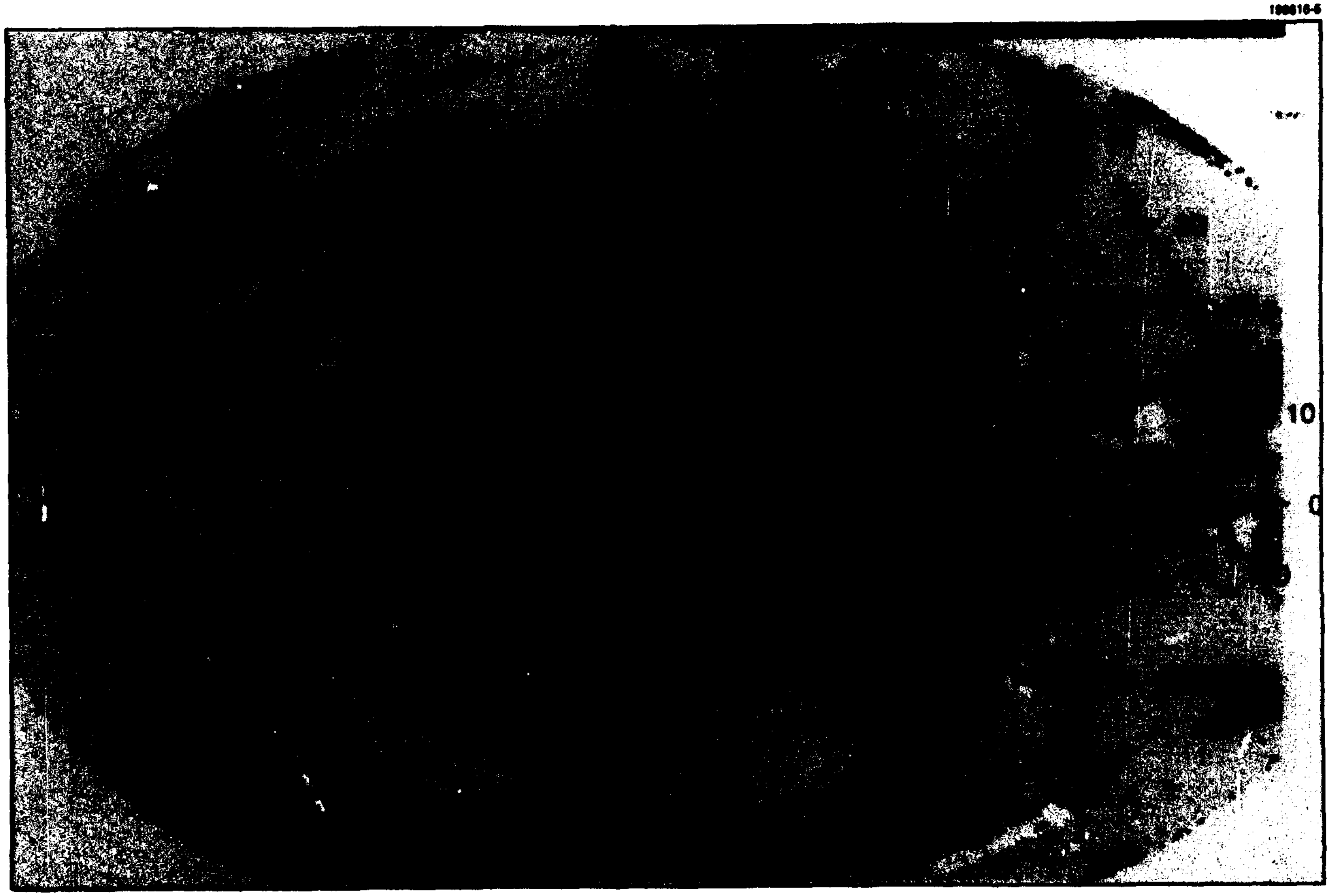

Figure 2(b). GMS IR full-disk facsimile image covering the western Pacific Ocean on 11 July 1991. Kwajalein is indicated at K; the area for which cloud statistics were derived is outlined.

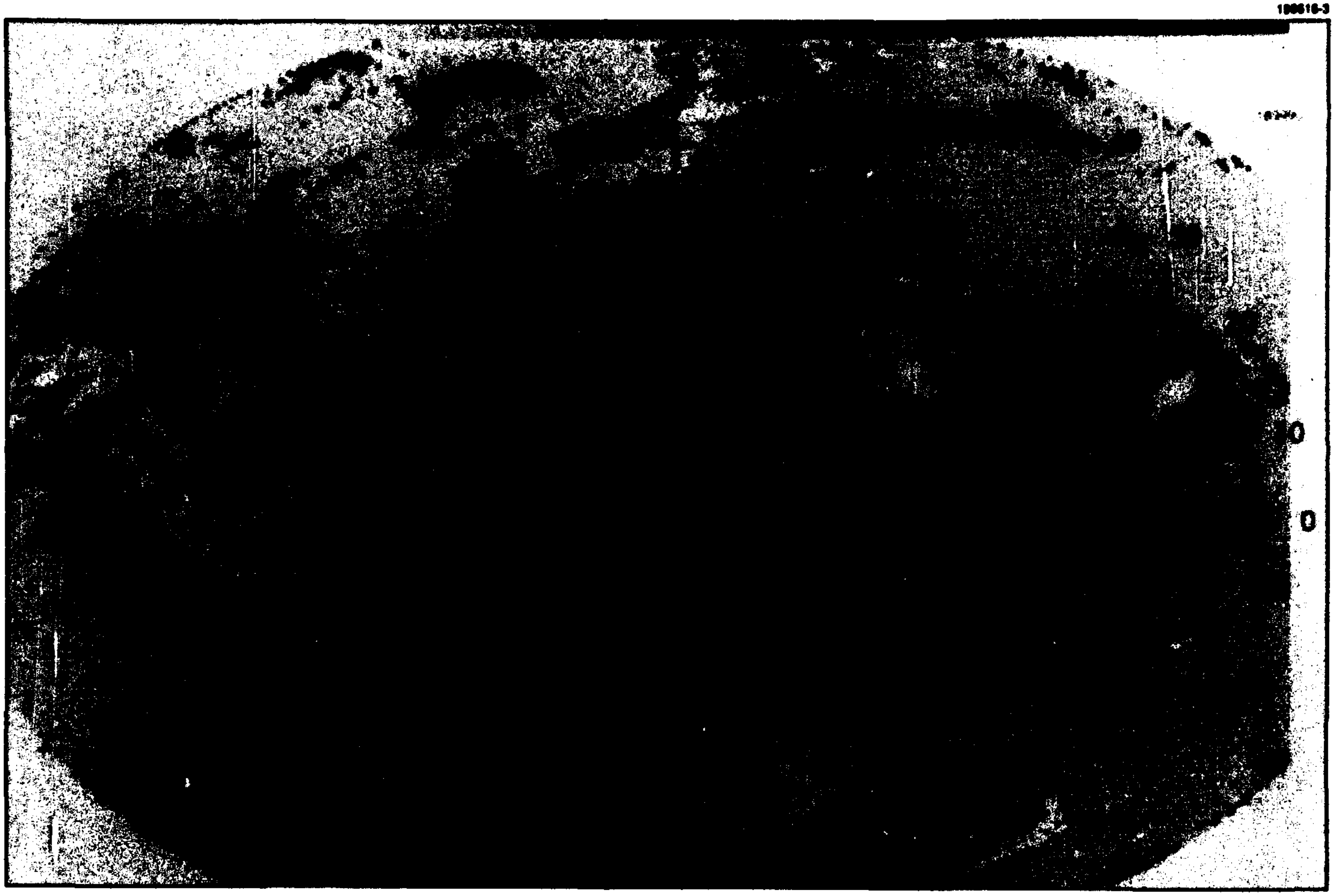

Figure 2(c). GMS IR full-disk facsimile image covering the western Pacific Ocean on 14 August 1991. Kwajalein is indicated at K; the area for which cloud statistics were derived is outlined.

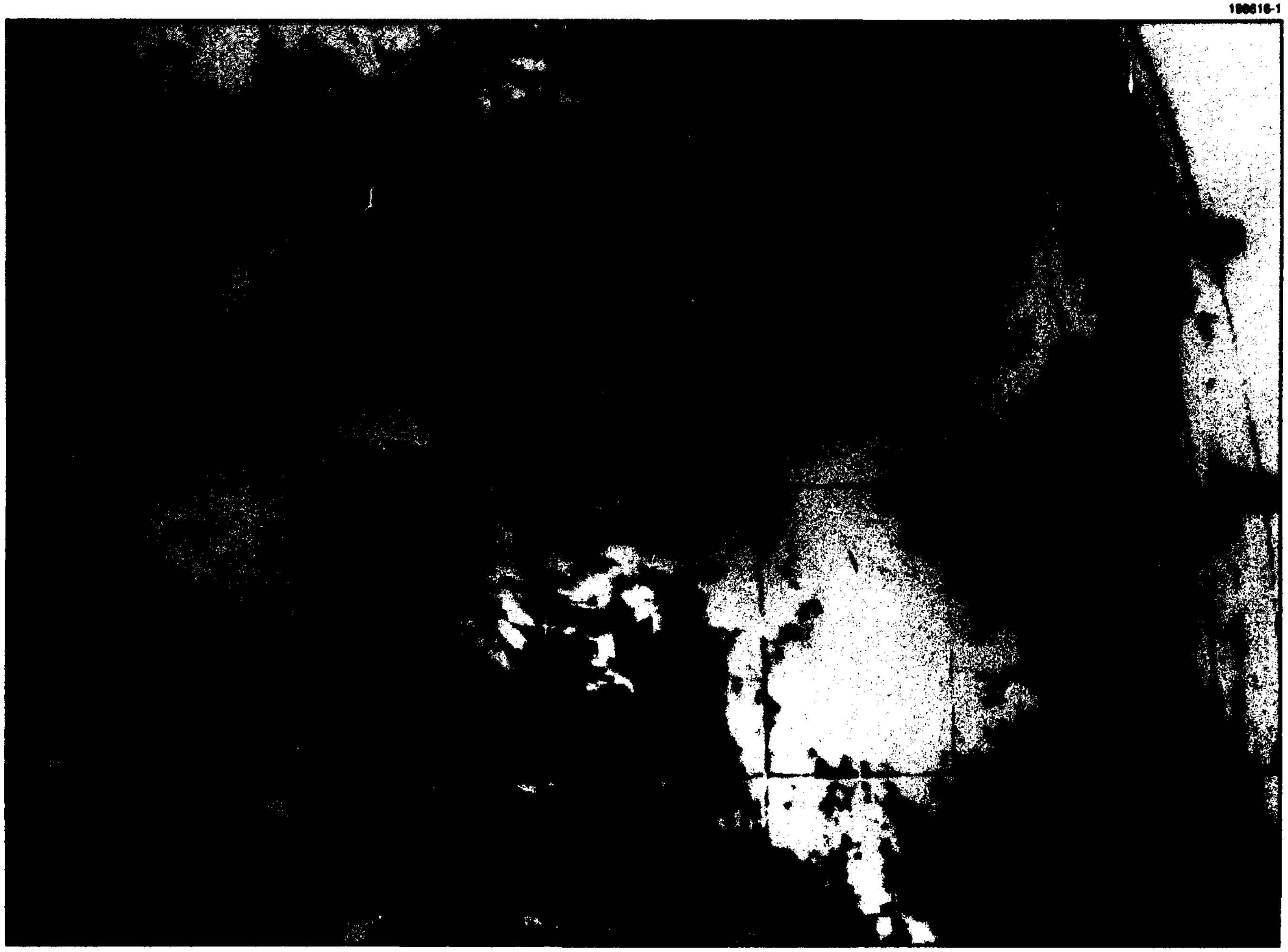

Figure 3(a). GMS full-resolution IR print showing cloud cover in the Kwajalein area on 29 May 1991. Kwajalein is indicated at K; the area for which cloud statistics were derived is outlined.

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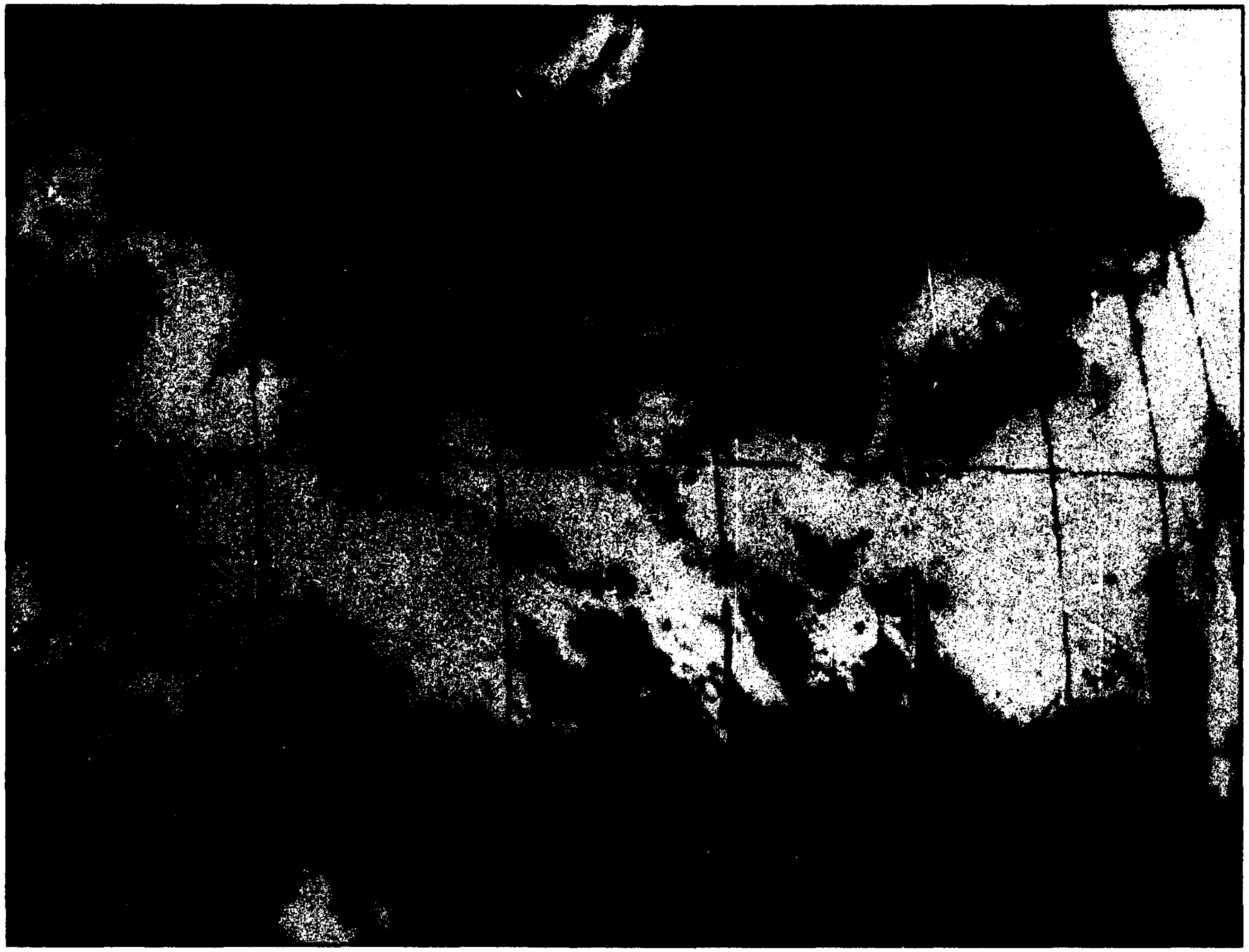


Figure 3(b). GMS full-resolution IR print showing cloud cover in the Kwajalein area on 5 June 1991. Kwajalein is indicated at K; the area for which cloud statistics were derived is outlined.

it is the "cap" for thunderstorm tops; cirrus clouds forming at the tops of thunderstorms ("anvil tops" to cumulonimbus clouds) do not often extend beyond the tropopause level because any moisture reaching into the stratosphere is dispersed by the extremely dry atmosphere. In this study, Bussey breaks down a cirrus cloud into layers to account for the large variations that can occur because tropical cirrus clouds may have bases at levels as warm as -28°C and tops near the tropopause at levels as cold as -65°C.

The moisture data in the Kwajalein ESI analysis were plotted in terms of "dew-point depression" because it is a good indicator of clouds. Bussey gives the following relationship between dew-point depression and cloud formation: depression of 0 to 3°C, high probability of clouds; 3 to 7°C, 50% probability of clouds; greater than 7°C, too dry for clouds except at high altitudes (at high altitudes, ice-crystal cirrus may exist with a dew-point depression as large as 10°C).

3.2 CLOUD MAPS OF THE PACIFIC OCEAN

3.2.1 Maps Derived from Early Satellite Imagery

In two studies of Pacific Ocean cloudiness [7,8], cloud amount maps were compiled from early satellite imagery for two sample periods: 1965 to 1972 and 1973 to 1978. These maps were compiled from operational nephanalyses averaged over 2.5° latitude-longitude squares; automated analysis methods could not be used because of too many variations in the satellite sensor systems during those periods. The satellite data used were one-per-day observations, visible data only (observation time at 1400 LST for the earlier sample period and 0900 LST for the later period). Although there are limitations in the use of early satellite observations, these maps of monthly mean cloud amounts represent the only extensive cloud mapping of the Pacific Ocean from satellite data and provide some useful climatological information of the cloud cover in the Kwajalein area.

Kwajalein, at 9.4°N, lies near the boundary between two overall cloud features described in these reports: the near-equatorial Maximum Cloudiness Zone (MCZ) to the south of Kwajalein, and the trade-wind zone of minimum cloudiness to the north. The data show that cloud areas do not always coincide with the zone known as the Intertropical Convergence Zone (ITCZ), so this report refers to the MCZ. Deep convective clouds are features of this zone throughout the year, and clouds within the zone are often organized in relatively narrow east-west bands. The data also show an area of maximum MCZ activity in the western Pacific to the west of Kwajalein (at 135° to 140°E); this area is more intense and moves farther east during summer. The minimum cloud zone has a southern boundary near 10°N, although the axis moves with season. The minimum cloud area also has longitudinal shifts centered farther west in October to May; this area moves eastward from August to September.

The mean monthly cloud amounts in the Kwajalein area range from 38 to 64% (3.1 to 5.1 oktas, the values represented in the maps). The overall monthly averages for the entire sample period (1965 to 1972) range from 44% (3.5 oktas) in February to 56% (4.5 oktas) in several months between June and October. In all months, lesser cloud amounts are mapped to the north and greater amounts to the south. Although no overall average maps are given for the later sample period (1973 to 1978), the charts of mean cloud amount for individual months show no significant difference from the earlier sample period.

The mean monthly cloud amounts derived from satellite observations show the same overall seasonal trends as the mean amounts given in the Kwajalein LCD (e.g., February is the least cloudy month in both data sets). The cloud amounts are considerably less, however, in the satellite charts; monthly means range from 44 to 56% as compared to the LCD values of 76 to 85%. As pointed out in this study,

the true cloud cover over the Pacific Ocean is hard to estimate because of the lack of real "ground truth." Nevertheless, the differences are probably due to a number of factors: the satellite maps are derived from early, less reliable satellite systems; the satellite maps are only one-time-per-day observations that are averaged over 2.5° latitude-longitude squares; the satellite maps are from visible observations only, so they may underestimate some types of clouds, especially thin cirrus; and the surface observations may overestimate cloud amounts, especially with the vertically developed clouds common in the tropics. It is likely, therefore, that the "true" cloud amount at Kwajalein may be somewhat greater than these satellite-derived cloud charts and somewhat less than the climatological surface observations.

3.2.2 Maps Derived from Ship Reports

In another approach to determining cloud distribution over oceans [9], maps of the global distribution of total cloud cover and cloud-type amounts have been derived from a 30-year sample of ship reports. These maps are complementary to cloud climatologies derived from satellite data, such as the above. In this study, all ship report data considered are from 1930 to 1981, with concentration on the 30-year sample (1952 to 1981). The average amount of cloud for six cloud types is given for each of the four seasons at the $5° \times 5°$ latitude-longitude resolution.

The method used in this study was designed to derive the true average cloud amounts rather than the amounts seen from below or above; the true average obtains separately the average frequency of occurrence and the average amount when present and multiplies these factors to derive the average amount of the cloud type. This study also discusses the difference between "sky cover" and "earth cover," where sky cover is what the ground observer reports, and earth cover is the fraction of the earth covered by clouds when projected vertically. The difference depends on the ratio of the vertical-to-horizontal dimension of the cloud, and except when there is 0 or 100% cloud, sky cover usually exceeds earth cover. Satellite observations are close to earth cover, but they still have some bias because of oblique viewing angles. However, satellites may provide more information about high clouds, whereas ground observers often have a better view of the low clouds.

The results of the study by Warren et al. [9] show the global average total cloud cover over oceans to be 64.8%. The overall cloud amounts derived from ship reports are slightly greater than the amounts derived from the early satellite imagery by Sadler et al. [7]. In the tropical Pacific, ship reports indicate that the greatest amounts of cumulus (about 20%) occur in the regions of trade winds (i.e., the region where Kwajalein is located). Cumulonimbus amounts are found to be greatest in the ITCZ, whereas nimbostratus is hardly ever reported at equatorial and subtropical latitudes. The largest amounts of cirrus occur in the subpolar and equatorial regions.

3.3 OCCURRENCE OF HIGH CIRRUS CLOUD IN THE KWAJALEIN AREA

The frequency of occurrence of high cirrus clouds in the tropics is of considerable interest. In the above study [9], data from ship reports indicate that large amounts of cirrus occur in equatorial regions, probably due largely to the spread of cumulonimbus cloud tops. In that report it is noted that cirrus is the only cloud type where less cloud is found over the ocean than over the land; Warren et al. believe this may be due to a difference in threshold optical thickness (i.e., because of the marine haze layer, cirrus has to be thicker to be detected over the ocean by a ground observer as compared to over land). Although the maps derived from ship reports provide valuable cloud information, ongoing data collection for

tropical ocean regions, such as the Kwajalein area, must rely primarily on satellite observations. As discussed in the report describing a cloud climatology of the North Pacific [2], however, some types of cirrus clouds either may not be detected or may be misrepresented by satellite sensors.

Because of the impact of thin cirrus on reentry vehicles, several studies of cirrus existence and probability of occurrence have been reported. In a study for the Kwajalein area by Burke et al. [10] the sensitivity of various remote-sensing techniques for quantitative measurements of thin cirrus clouds was evaluated. This study used theoretical calculations to predict the minimum detectable density and number of ice crystals for ground observations, eyeball observations (at aircraft altitudes of 8 to 10 km), and satellite IR sensors (at 6.7 μm). The model assumed a 1-km-thick (13 to 14 km) cirrus layer in a tropical atmosphere (to represent the Kwajalein area).

The results of this study show that thin cirrus cloud detected from aircraft observations or from IR sensors on board satellites can be invisible from the ground. However, the required concentration of ice particles to detect a "severe clear" situation (i.e., a situation where particles larger than 80 μm occur in concentrations of less than 1 m^3) is a threshold too low for virtually all existing sensors. These results indicate the difficulties in detecting thin cirrus cloud whether by a ground observer or from satellite sensors.

In the Burke et al. report [10], the results of a statistical study of the probability of severe-clear versus tenuous cirrus are also presented. The statistics are derived from a one-year (1975) sample of cross-section analyses drawn for Kwajalein from surface observations, upper air soundings, satellite observations, and radar reports. The event was considered tenuous cirrus if it was immediately before or after a report of cirrus (i.e., requirement for clearing the atmosphere of lingering crystals) or if convective activity was reported in the Kwajalein area. A case was determined to be severe-clear if it was not tenuous cirrus and the upper atmosphere (10- to 17-km level) was dry (dew-point depression 10°C or greater); a no-cirrus case was determined from surface reports and dew-point depression. The results show relatively low probabilities of any of these events occurring (no cirrus, tenuous cirrus, severe-clear). The probability of no cirrus is greater than 10% in only four months out of the year, whereas the probabilities of tenuous cirrus or severe-clear exceed 10% for only three months. The probabilities are greatest in March with no cirrus being nearly 40%, tenuous cirrus 10%, and severe-clear 27%; the second highest probabilities occur in December. Although only a one-year sample, the results imply a high probability of occurrence of some type of cirrus cloud in the Kwajalein atmosphere.

Another discussion of cirrus cloud and the problems in its detection is given in a report by Bauer et al. [11]. The findings in the Bauer report are helpful for interpreting the Kwajalein cloud statistics, particularly because Bauer also examined data from the Air Force 3D-NEPH model, the same data base as used to develop the Kwajalein cloud climatology. Pertinent results from the Bauer study are discussed in the following paragraphs.

The optical properties of clouds are discussed in the report because detection of clouds by satellite sensors is impacted greatly by optical thickness. Low clouds (at 1- to 3-km heights, containing liquid water, high temperature) are optically thick; high clouds (at 5- to 10-km heights, small ice/water content, low temperature) are optically thin. Cumulus and stratus clouds are examples of optically thick clouds, whereas cirriform clouds, including cirrocumulus and cirrostratus, are frequently optically thin. Cumulonimbus clouds are optically thick but may rise to high altitudes and have cirrus tops. The dividing line between water and ice clouds is about -20°C (253 K); clouds at altitudes of less than 3 to 5 km usually have temperatures higher than -20°C and are water-droplet clouds.

Based on early 3D-NEPH data (1972 to 1975), it appears that the 3D-NEPH data base may significantly underreport very thin clouds because of sensor limitations. In general, the 3D-NEPH data base reports clouds with emissivity ≥ 0.7 at correct altitudes but reports clouds with emissivity < 0.7 but ≥ 0.3 at too low altitudes; clouds with emissivity ≤ 0.2 may not be detected at all and thus not be reported in the data base (it is pointed out that later 3D-NEPH data may do better).

With regard to cloud altitudes, the range of altitude for three cloud types is given as follows: nimbostratus: 0.1 to 3 km, fair-weather cumulus: 0.3 to 5 km, and cirrus: 4 to 15 km. The most probable height of cirrus is estimated to be about 1 km below the level of tropopause, with tropopause levels at 8.5 km for subarctic winter, 11 km for midlatitude, and 16 km for the tropics. A study of cirrus in the USSR, using ground-based and satellite observations, showed cirrus as having a mean base height of 7.2 km and a mean vertical thickness of 2 km. Cirrus altitude ranges (from various sources) are summarized in the Bauer report, as depicted in Table 2.

The frequency of occurrence of high-cloud and total-cloud cover derived from the 3D-NEPH data base is given for a number of locations. The high clouds are those at altitudes >7 km, with heights determined by comparing cloud-top temperatures with atmospheric temperature profiles; thus, the high clouds are thicker cirrus and cumulonimbus. Although no equatorial sites are listed, the frequency of occurrence of high/total cloud for Maui (at 21°N) is given as 0.14/0.40 (January) and 0.12/0.50 (July). It is of interest that the total cloud amounts (40 to 50%) are very close to the values given by Sadler (see Section 3.2), which were also derived from an early satellite data set. The overall frequency of occurrence of cirrus clouds based on all available data sources is considerably greater than the 14 and 12% values for Maui obtained from the 3D-NEPH data base. The study of cirrus in the USSR, for example, shows cirriform clouds occurring about 50% of the time. The overall estimate, according to the Bauer report, is that cirrus occurs worldwide 30 to 50% of the time with a somewhat greater frequency in the ITCZ where Hadley Cell upwelling transports warm, moist tropical air into the cold tropical tropopause region, which leads to the formation of relatively greater amounts of cirrus.

TABLE 2
Cirrus Cloud Altitude

Region	Altitude (km)
Tropics	7.5 – 16.5
Temperate Summer	7.3 – 13.5
Temperate Winter	4.5 – 14.0
Polar Summer	4.5 – 9.5
Polar Winter	2.5 – 10.0
USSR Summer	8.0 – 10.0
USSR Winter	6.5 – 8.5

A recent report by Edelberg [12] discusses the occurrence of cirrus cloud in the tropical Pacific based on statistics derived from three different satellite systems and from long-wave infrared (LWIR) measurements from aircraft. The existence of cirrus cloud in the tropics is a serious problem for data collection on reentry vehicles because cirrus can occur above aircraft altitudes (as high as 15 to 16 km) and therefore obscures aircraft-upward-viewing LWIR sensors. The cirrus cloud statistics were derived from the 3D-NEPH model (DMSP data base), as well as the Nimbus-5 and Applications Explorer Mission-2 (AEM) satellites. The DMSP data base (1977 to 1983) gave statistics for cloud occurrence at the highest 3D-NEPH layer (above 35,000 ft) in terms of frequency of occurrence, mean cloud amount, and cloud-free line-of-sight (CFLOS). The statistics indicate slightly less cloud at night and overall less cloudiness the last five months of the year than for the first seven months (the differences, however, are relatively small, in most cases being only a few percentage points). For the August–December period, the statistics show cloud-free conditions 65% of the time and completely cloud covered 11% of the time; the mean cloud amount is 24%.

The Nimbus-5 data sample (1972 to 1975) is from the Selective Chopper Radiometer (SCR), which gave global high-cloud distribution derived from measurements in two IR channels. The distributions show the least cloudiness in the tropical Pacific from December to February, with a frequency of less than 20% at latitudes north of 10°; the cloud frequency increases from 20 to 40% between March and November.

The Stratospheric and Gas Experiment (SAGE) on the AEM-2 satellite (1979 to 1981) also provided vertical profiles of cirrus cloud by measuring in a band at 1.0 μm. The SAGE measurements, considered more sensitive than the SCR, show cirrus 20 to 40% of the time during September–November at latitudes north of 10° and east of 167°E; the same frequencies are found during December–February north of 15° and east of 167°E. Frequencies as high as 60% occur near Kwajalein in the March–April period.

The report concluded that the cirrus cloud statistics from the three satellite data bases are fairly consistent. The period with the least cirrus cloud near Kwajalein is September to February. During this period, the frequency of thick cirrus is near 20%; the frequency of thin cirrus is smaller by a factor of 2 or more; the frequency of large-scale cirrus is of the order of 30%; and the area with the least occurrence of cirrus is several hundred miles north and east of Kwajalein. The period with the greatest occurrence of cirrus is March to August when the frequency of thick cirrus is about 30% and the frequency of large-scale cirrus is about 60%. These satellite results were also consistent with the Project PRESS airborne LWIR data collection.

4. CLOUD CLIMATOLOGY STATISTICS

4.1 PRESENTATION OF CLOUD STATISTICS

The mean cloud amount and cloud amount frequency of occurrence statistics are presented in Appendices A and B, respectively, for low-, middle-, and high-cloud layers. The statistics are presented in graphical format for all 31 grid-point locations (30 locations at 5° × 5° grid points and Kwajalein) for the four representative months (January, April, July, and October). In Appendix A, each page displays the mean cloud amount plots for the six longitude locations (155°E to 180°) along a single latitude; the plot for Kwajalein is shown separately. In Appendix B, each page displays the cloud amount frequency of occurrence plots for a single grid-point location.

The cloud statistics presented in the appendices are for the noon observation time. A subset of data was initially run for both the noon and midnight observation times to examine the diurnal variation in cloud amount. Although the local climatological data for Kwajalein [5] indicates very little difference between the overall monthly mean cloud amounts and the cloud amounts for just the daylight hours, the study by Edelberg [12] does indicate less cloud at night at Kwajalein. The statistics used in the current study also indicate slightly less cloud at night, but the day-night differences in mean cloud amount do not appear to be significant, particularly when the inherent limitations of the data base are taken into account; therefore, only the noontime data are presented in the report.

The cloud statistics also are presented only for three cloud layers (low, middle, and high clouds). After acquiring the additional data set, the mean cloud amounts for the additional six upper cloud layers were compared with the mean cloud amounts for the single high-cloud layer. The cloud amounts for the separate layers did not appear to be significantly different than the amounts for the overall high-cloud layer. Realizing also that errors in the data base tend to be greater for high clouds (see discussion in Section 3), it was decided that inclusion of the statistics for the additional cloud layers would not provide additional useful information.

The mean cloud amount graphs (Appendix A) consistently show the greatest cloud amounts in the low-cloud layer and the least cloud in the high-cloud layer. The exception is the graph for Kwajalein, where the mean cloud amounts for the three cloud layers are about the same percentages for each month. Compared to the other locations at the same latitude (10°N), the Kwajalein graph shows somewhat less cloud in the low-cloud layer, but significantly greater cloud amounts in the high-cloud layer; the middle-cloud amounts are about the same at Kwajalein as the other locations.

Some differences in cloud amount are observed over the four months shown in the displays, but the amount of seasonal variation is relatively small. At 10°N, January is the least cloudy month and July and October the most cloudy; the same trend is observed at Kwajalein. The seasonal variations for the locations at 15°N are similar, although October has somewhat less cloud at some locations; less seasonal variation is evident at 20°N, with both January and October having slightly smaller cloud amounts. At both 0° and 5°N, no significant month-to-month differences are evident. Overall, the observed seasonal variation in cloud amount is small enough that it is doubtful whether any other month would be significantly different from the representative months of January, April, July, and October.

The latitudinal variations in mean cloud amount are in good agreement with what would be anticipated from climatological considerations. Much less cloud is observed at 20°N in all four months, with amounts being in the range of 20 to 30% (low cloud), 10 to 20% (middle cloud), and 0 to 10% (high cloud). Somewhat greater cloud amounts occur at 15°N, and significantly more cloud is observed at 10°N; cloud amounts at the locations along 10°N are in the range of 40 to 60% (low), 20 to 40% (middle), and 5 to 25% (high). At Kwajalein (9.4°N), the high-cloud amount is in the range of 30 to 44%. The greatest mean cloud amounts are found along 5°N, with amounts in the range of 50 to 70% (low), 35 to 55% (middle), and 20 to 30% (high); slightly less cloud is observed at 0°. No significant longitudinal variation in mean cloud amount is observed except at 0°, where greater cloud amounts occur at the locations west of 170°E; the difference between the locations at 155°E and 180° is the most pronounced.

The cloud amount frequency of occurrence graphs (Appendix B) are displayed in five categories: no cloud (clear), 5 to 35%, 40 to 65%, 70 to 95%, and 100% (overcast). These graphs show the same overall trends as the mean cloud amount graphs. The locations at 20°N show a high percentage of the clear category at each cloud level, with nearly all observations of high clouds being clear during some months. The locations at 5°N show a much more even distribution, although "clear" is still the greatest percentage at the high-cloud layer; for low clouds, the categories other than clear have higher frequencies of occurrence.

4.2 DISCUSSION OF CLOUD STATISTICS

The cloud statistics for the Kwajalein area (equator to 20°N, 155°E to 180°) are consistent overall with other data sources and with climatological considerations, showing that there is much less cloud cover to the north of Kwajalein and greater amounts of cloud cover to the south in all seasons. The seasonal variation in cloud amount is small and not consistent from location to location. Although for the locations at 10°N and for Kwajalein (9.4°N), January is the least cloudy month and July and October are the most cloudy. This seasonal trend is in agreement with other data sources for Kwajalein that show January and February as the least cloudy months.

It is difficult to compare this cloud climatology directly with the climatologies derived from earlier satellite imagery [7,8] or from ship reports [9] because of the different methods used to categorize cloud types and layers. For example, the cloud amounts for the 3D-NEPH high-cloud layer for the Kwajalein location are greater than the amounts for cirrus derived from the ship report data base; if cirrus and cumulonimbus are added together, then the amounts are in fairly close agreement. On the other hand, for the other data locations near Kwajalein, the 3D-NEPH high-cloud amounts are about the same as the cirrus amounts from ship reports; if the cirrus and cumulonimbus amounts are added together, their total amounts generally exceed the 3D-NEPH high-cloud amounts. In their discussion of the assumptions for estimating middle and high clouds, Warren et al. [9] compared their data with a limited sample of 3D-NEPH data and found the agreement to be quite good.

Some differences in the Kwajalein cloud climatologies derived from this data base and from other data sources discussed in Section 3 are apparent. For example, the Local Climatological Data Summary (LCD), based on surface observations, shows almost no month-to-month variation in cloud amount, whereas some of the studies do show monthly differences. The study of thin cirrus over the tropical Pacific by Burke et al. [10] using one year of data indicated that March had the smallest frequency of occurrence of cirrus, whereas the data set used by Edelberg [12] showed March and April as being the

most cloudy months. These apparent discrepancies may occur because the month-to-month variation in tropical cloudiness is relatively small, so the localized year-to-year variations for a given month may be of the same magnitude as the month-to-month variations.

Because the study by Edelberg [12] and this current study have used similar data sets (3D-NEPH data provided by the Air Force ETAC), it is of interest to compare the results. It should be noted that the purposes of the two studies are somewhat different. This data set is for Kwajalein and 30 grid locations within approximately 1000 km of Kwajalein; the actual location of Kwajalein used in this data set is Roi Namur at the northern tip of the Kwajalein Atoll (9.4°N, 167°E). The data set used by Edelberg is for a single location (8.36°N, 167°E), the location of the Kwajalein reporting station at the southern tip of the atoll. Also, this data set is for low-, middle-, and high-cloud layers, with the high-cloud layer being everything above 5.2 km (see Section 2.1.2); the Edelberg data set is only the highest 3D-NEPH cloud layer (10.7 to 16.7 km).

When comparing the two data sets, the manner in which the 3D-NEPH data base is compiled must be kept in mind. The 3D-NEPH data base is an operational product derived from DMSP satellite data together with input from other data sources [1]. The integration of conventional observations with the satellite data is discussed further in a report by Kiess and Cox [13] that describes the Air Force Automated Real-Time Cloud Analysis Model. Although this report is on the RT-NEPH, many of the RT-NEPH procedures are the same as were used in the 3D-NEPH model (the major RT-NEPH differences are in the data base definition of the vertical structure and in the addition of diagnostic information). The report points out that the RT-NEPH

> ... continues to blend high-resolution satellite data and conventional data to perform an automated cloud analysis.... The conventional observations may include surface reports, upper-air data, and/or aircraft reports from the Air Force GWC data base; a decision-tree processor integrates the various data sources, and a cloud layer may be derived from the satellite data or from conventional data.

Because of the integration of satellite and conventional data sources, the 3D-NEPH data base for a location that corresponds to a reporting station, such as Kwajalein or Roi Namur, may include surface reports and upper-air data as well as satellite data. At other grid-point locations, however, the data base may be derived from satellite data alone or possibly from satellite data together with some aircraft reports. A comparison of cloud statistics for Kwajalein, Roi Namur, and a nearby grid-point location is shown in Table 3.

The mean cloud amounts for the two Kwajalein locations in the two data sets are in close agreement, although Edelberg's statistics for "A" show January to have more cloud than October, whereas the statistics for "B" show October to be cloudier than January. With regard to frequency of occurrence of cloud amount, the Edelberg statistics are apparently more U-shaped than the statistics for Roi Namur because the frequencies of occurrence of both clear and overcast are greater in all four months.

The mean cloud amounts at the 10°N, 165°E location "C" are significantly lower than either of the two Kwajalein locations. At "C," January is much less cloudy than October. The frequency of occurrence of clear is very high at "C," except in October where the Edelberg statistics have a slightly higher frequency. The frequency of occurrence of overcast is extremely low at "C" in all four months. The small cloud amounts at the 10°N, 165°E location again point out the limitations of satellite observations alone in detecting high (cirrus) cloud. As indicated in the statistics for the Kwajalein locations and from other studies discussed in Section 3, such as Bauer et al. [11], the frequency of occurrence of cirrus cloud in

the tropics may be quite high. It appears, therefore, that although the lower layer cloud amounts may be fairly accurate at the grid-point locations where satellite observations are the only data source, the high cloud amounts are likely to be underestimated. From previous discussions in Barnes et al. [2] it was believed that cirrus cloud amounts at higher latitudes might be underestimated in the 3D-NEPH data set by about 10%. The Kwajalein statistics indicate that in the tropics, the occurrence of high cirrus cloud may, in fact, be as much as 20% greater than that indicated in the satellite-derived data base.

TABLE 3
Comparison of Kwajalein Cloud Statistics for Three Locations

Mean Cloud Amount (In Percent)

Month	A	B	C
January	39	32	6
April	38	38	11
July	41	44	17
October	33	44	21

Frequency of Occurrence of Cloud Amount (In Percent)

	Clear (0 percent)			Overcast (100 Percent)		
Month	A	B	C	A	B	C
January	50	41	78	26	9	2
April	53	31	67	24	12	1
July	47	26	61	21	11	4
October	55	27	52	17	14	4

Key
A – Kwajalein (8.36°N, 167.36°E) for cloud layer 10.7 to 16.7 km (Daytime) [12]
B – Kwajalein (Roi Namur at 9.4°N, 167.5°E) for cloud layer above 5.2 km (Noon)
C – Grid-Point Location (10.0°N, 165.0°E) for cloud layer above 5.2 km (Noon)

Although the cirrus cloud statistics derived solely from satellite data (i.e., for ocean locations where no other observations are available) may be inadequate and the occurrence of high cirrus may compromise LWIR data collection from aircraft platforms, cirrus does not pose a significant problem on the estimation of LWIR upwelling earthshine computations.

4.3 ONGOING CLOUD DATA COLLECTION PROJECTS

As seen in the previous section, many cloud data sets for the tropical Pacific are for relatively short periods and are not from ongoing data-collection projects. The maps derived from 30 years of ship reports represent the longest sample period. At this time, the only readily accessible data base that provides statistics for cloud layers is the 3D-NEPH model. When the limitations are recognized, this data set does provide useful statistics for assessing cloud conditions in the Kwajalein area.

The RT-NEPH model, discussed in the previous section, will provide an increasingly longer period data base for cloud studies. This model has been in operational use by the Air Force since 1983 and provides a much finer breakdown of vertical cloud layers than the 3D-NEPH model. The RT-NEPH data are still in the process of being summarized, however, so it is not yet available in a readily usable format like the 3D-NEPH.

The most comprehensive project to produce a global cloud climatology is the International Satellite Cloud Climatology Project (ISCCP) of the World Climate Research Program (WCRP). The current status of the ISCCP is reported in a paper by Rossow and Schiffer [14]. The data and products of the ISCCP are described in the data catalog [15]. The ISCCP collection period is 12 years (July 1983 through June 1995).

The scientific objectives of the ISCCP are

1. To produce a global, reduced resolution, infrared and visible, and calibrated and normalized radiance data set containing basic information on the radiative properties of the atmosphere from which cloud parameters can be derived.
2. To stimulate and coordinate basic research on techniques for inferring the physical properties of clouds from the condensed radiance data set and to apply the resulting algorithms to derive and validate a global cloud climatology for improving the parameterization of clouds in climate models.
3. To promote research using ISCCP data in contributing to an improved understanding of the earth's radiation budget (top of the atmosphere and surface) and of the hydrological cycle.

Although the objectives of the project are not designed to produce a data base for compiling a cloud climatology for a particular area such as Kwajalein, some data products may have future use in cloud studies for Kwajalein or other areas. The ISCCP data sets include data from the GMS satellite, so the tropical Pacific is covered. An example of one of the products available from the GMS is the B-1 data set, which is a set of radiance data at 10-km resolution. A difficulty in working with this data set is the enormous volume of data (each data tape contains only about eight days of data).

The most useful ISCCP products for projects such as the Kwajalein study are the cloud climatology product (C) data sets. The C-1 data sets are global merge sets, reported every three hours at a spatial resolution of 250 km. These data sets can be acquired in equal latitude-longitude map grids with 2.5° increments; therefore, a set of C-1 data could be acquired for a selected number of 2.5° increments to cover an area centered on Kwajalein or some other location of interest.

Another of the cloud climatology products is the C-2 data set, which consists of monthly averages and summary statistics of the stage C-1 quantities. When these products are generated, they will provide a more compact summary of the cloud results (two years of C-2 data will be contained on a single CCT). Because of the more manageable data amount, this product may be the most useful for input to an area-specific cloud climatology.

5. ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES

5.1 TEMPERATURE PROFILES

The atmospheric temperature and moisture profiles are presented in Appendix C for Kwajalein and for 28 other 5° × 5° latitude-longitude locations; the atmospheric profile data set did not include data for two locations in the southeast corner of the study area (0°, 175°E and 0°, 180°). The temperature profiles appear very reasonable from climatological considerations with the surface temperatures and the heights and temperatures of the tropopause about what would be anticipated for the tropics. Overall, there is little variation by month or location, although the surface temperatures are slightly lower at 20°N (temperatures are 18 to 25°C at 20°N; 25 to 28°C at the equator); the January surface temperatures are also slightly lower at 20°N.

The tropopause is at a height of 15 to 18 km at all locations. It is slightly higher and colder in January. In most months, the tropopause is sharply defined at 15 km at a temperature of -70°C. In January, it is as high as 18 km and as cold as -75°C; however, even in January a change is also apparent in the temperature gradient at the 15-km level. Except very near the surface at 20°N, the temperature profiles between the surface and tropopause show very little seasonal variation; above the tropopause, temperatures are somewhat colder in January.

5.2 MOISTURE PROFILES

As mentioned in Section 2.2, the moisture profiles needed to be converted from absolute humidity to dew point and then to dew-point depression (see Appendix C). Actually, in discussions with personnel at the Air Force ETAC, it was learned that these moisture data had originally been in dew-point values but had been converted to absolute humidity for a particular application. Undoubtedly, some error resulted from the conversion to absolute humidity and back to dew point. These possible errors, together with the inherent difficulties in measuring moisture, result in the moisture data being less reliable than the temperature profiles. Moreover, even in the tropics, the moisture data only extend up to the 300-mb level (about 9 km).

The moisture profiles in general display too much variation, some of which appears extreme and unrealistic, to determine any geographic or seasonal differences. Nevertheless, several of the profiles (i.e., at 20°N, 175°E) are in good agreement with climatological considerations; in the trade-wind belt, the atmosphere would be expected to be moist (dew-point depression less than 5°C) up to the 2-km level and dry above that level [5].

6. ESTIMATION OF CLOUD-TOP HEIGHTS AND TEMPERATURES

The 3D-NEPH data base provides cloud statistics for three layers: low clouds (surface to 1.9 km), middle clouds (1.9 to 5.2 km), and high clouds (above 5.2 km). The 3D-NEPH cloud heights agree closely with standard cloud charts for the tropics, which indicate the tops of the low-cloud layer at 2 km and the middle-cloud layer at 5 to 6 km. For the low- and middle-cloud layers, therefore, the cloud-tops can be estimated to be at the heights of the tops of the respective layers, and the cloud-top temperatures can then be estimated from the temperature profiles.

Although the high-cloud layer does not have a specific upper limit in the 3D-NEPH data base, the height of the top of the highest cirrus layer can be estimated from the tropopause level. Bussey [6] points out that the tropopause, which is at the 16- to 17-km level in the tropics, is the "cap" for cumulonimbus cloud tops (i.e., cirrus resulting from the spread of cumulonimbus anvil tops). Bauer et al. [11] gives the range for cirrus in the tropics as 7.5 to 16.5 km and states that the most probable height of cirrus is about 1 km below the tropopause (the tropopause being at 16 km). The atmospheric profiles for the Kwajalein area indicate the tropopause level at 15 to 18 km, which is in good agreement with the above studies; a height of 15 km, therefore, appears to be a very reasonable estimate for the top of the highest cloud (cirrus) layer.

As noted by Bauer, however, the range for cirrus in the tropics is considerable (7.5 to 16.5 km). Under certain conditions, therefore, it could be possible for a lower layer of cirrus to exist. If the typical thickness of a cirrus layer is assumed to be about 2 km, it would be unlikely that the top of a tropical cirrus layer would be lower than 10 km at the lowest. Thus, the range of cirrus cloud-top heights in the Kwajalein area is estimated to be 10 to 15 km.

The temperature profiles exhibit very little variation from location to location or from month to month. Therefore, the cloud-top temperature estimates apply to the entire Kwajalein area during all seasons. Only at 20°N are temperatures in the lowest levels slightly lower in January. The cloud-top height and temperature estimates for the three cloud layers are given in Table 4.

TABLE 4
Estimated Cloud-Top Heights and Temperatures for the Kwajalein Area

Cloud Layer	Height of Cloud Tops (km)	Temperature of Cloud Tops (°C)
Low Cloud	1.9	18
Middle Cloud	5.2	0
High Cloud	10 to 15	-35 to -70

7. CONCLUSIONS

A cloud climatology for the Kwajalein area in the tropical Pacific presents cloud statistics for Kwajalein (9.4°N, 167.5°E) and 30 locations within approximately 1000 km of Kwajalein. The statistics are derived from a five-year sample (1977 to 1983) of the Air Force 3D-Nephanalysis Global Cloud Archive (3D-NEPH model). Mean cloud amounts and cloud amount frequencies of occurrence are presented for four representative months and for three cloud layers: low (0 to 1.9 km), middle (1.9 to 5.2 km), and high (>5.2 km). Cloud-top heights and temperatures are also estimated from atmospheric profile data. The cloud climatology presented in this report updates previous climatologies and presents cloud statistics for Kwajalein and the surrounding area in a format usable for determining LWIR upwelling earthshine, which is a key element for data analysis of missile systems reentering the atmosphere.

Although it is difficult to compare this cloud climatology with other climatologies because of the different data sources, as well as the different methods used to categorize cloud types and layers, the cloud statistics for the Kwajalein area are consistent overall with other statistics and with climatological considerations. The statistics show that there is much less cloud to the north of Kwajalein and greater amounts to the south in all seasons; January is indicated to be the least cloudy month at Kwajalein, although the seasonal variations in cloudiness are relatively small. The mean cloud amount statistics for nearly all locations show the greatest cloud amounts in the low-cloud layer and the least cloud amounts in the high-cloud layer; the exception is Kwajalein itself, where the mean cloud amounts for the three layers are about the same percentages.

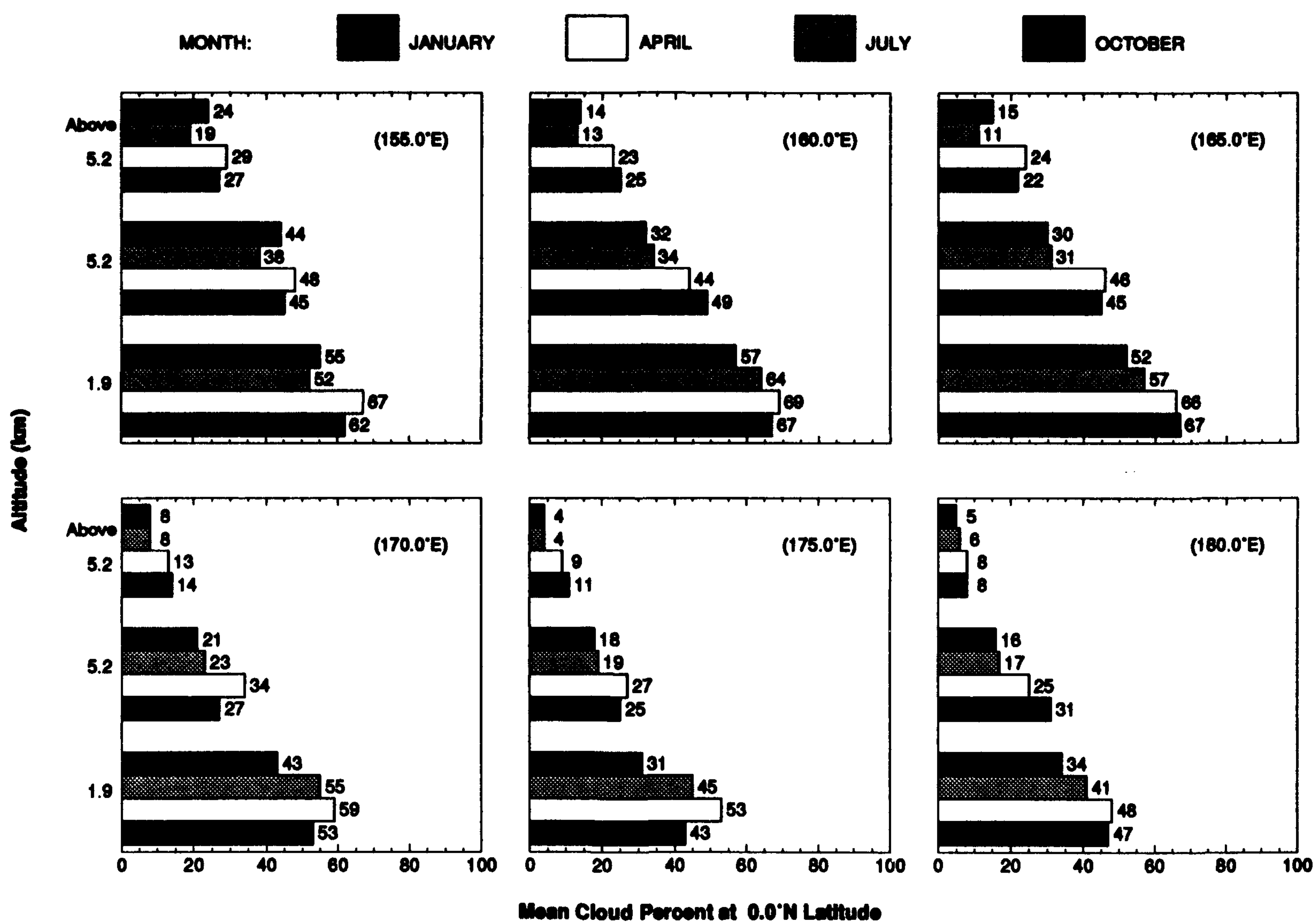
The comparison of this cloud climatology with the results of other studies, as well as the comparison between the statistics for Kwajalein and the other locations, indicates that the 3D-NEPH data base may underestimate the amount of high cloud (cirrus) by as much as 20% for the locations where the model uses only satellite data as input (the 3D-NEPH model integrates satellite and conventional observations to perform an automated cloud analysis; therefore, the cloud layers at a location coinciding with a reporting station, such as Kwajalein, will be determined from other observations together with satellite observations, whereas the cloud layers at a location over the ocean may be determined from satellite observations alone). However, whereas the cirrus cloud statistics may be inadequate and the occurrence of high cirrus may compromise LWIR data collection from aircraft platforms, cirrus does not pose a significant problem for LWIR upwelling earthshine computations.

The Air Force 3D-NEPH archive was the only readily available source of cloud data for the Kwajalein area, and the resulting cloud climatology is concluded to provide meaningful statistics when the inherent data limitations are taken into account. The more recent RT-NEPH data base will eventually provide improved cloud statistics when these data become available in the easily usable, summarized format. Also, some of the products from the International Satellite Cloud Climatology Project (ISCCP), a comprehensive program to produce a calibrated and normalized global data set, will have application for developing a better understanding of cloud cover in remote areas such as the tropical Pacific.

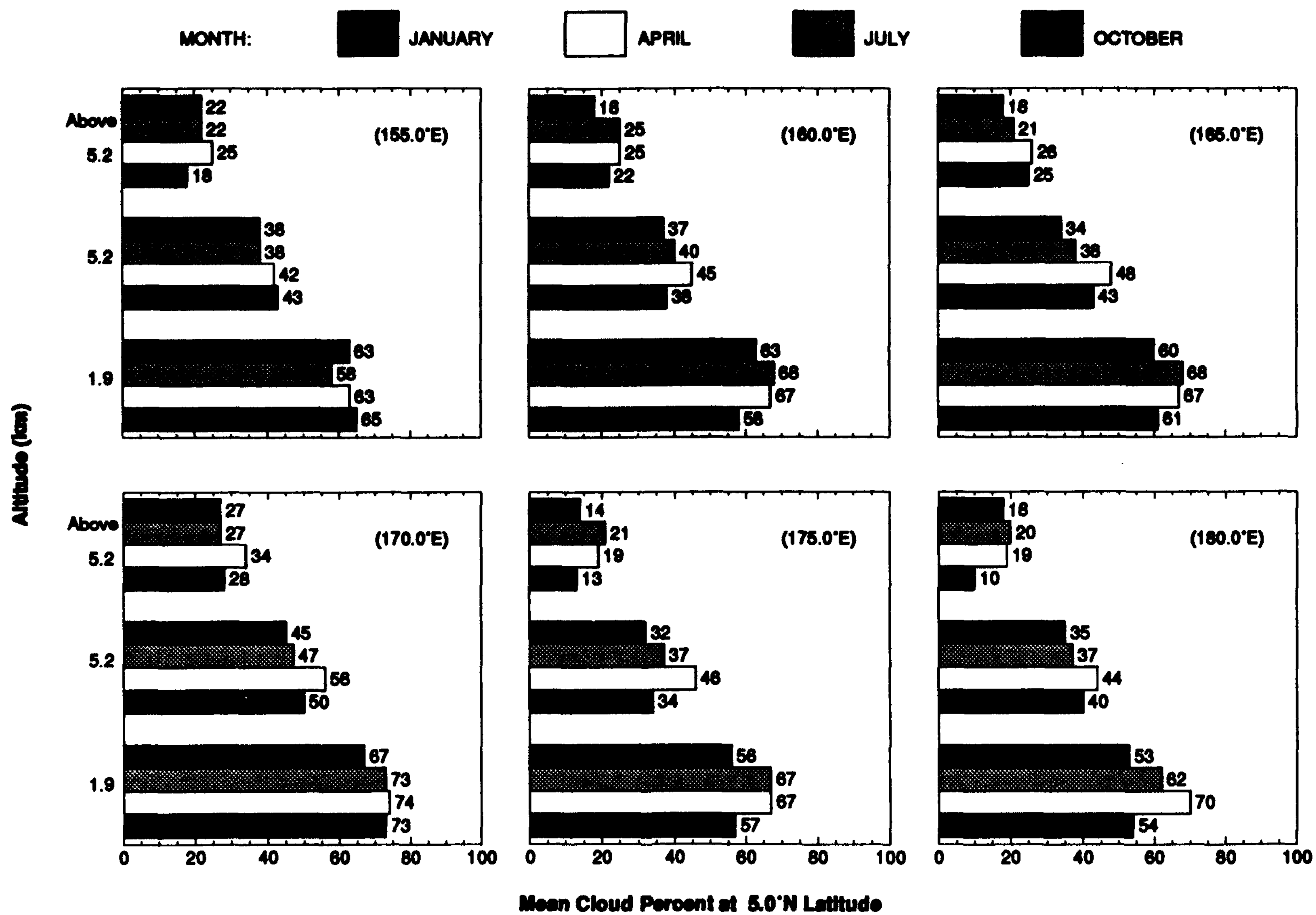
APPENDIX A

MEAN CLOUD AMOUNT (In Percent) FOR LOW, MIDDLE, AND HIGH CLOUDS

Mean Cloud Amount (in Percent) for Low (Surface - 1.9 km), Middle (1.9 - 5.2 km), and High (above 5.2 km) Clouds

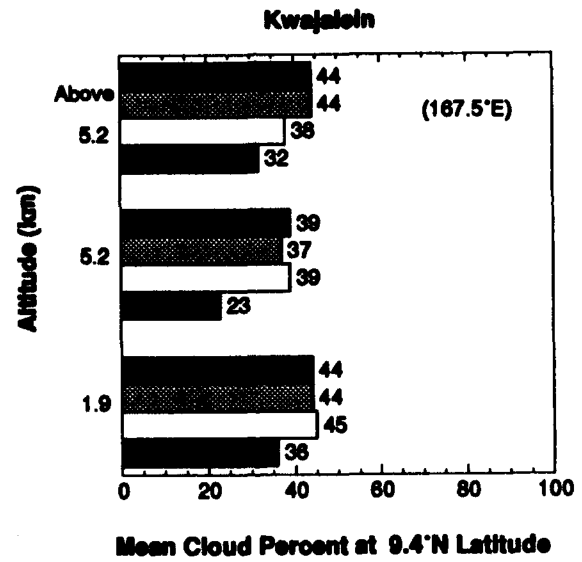


Mean Cloud Amount (in Percent) for Low (Surface - 1.9 km), Middle (1.9 - 5.2 km), and High (above 5.2 km) Clouds

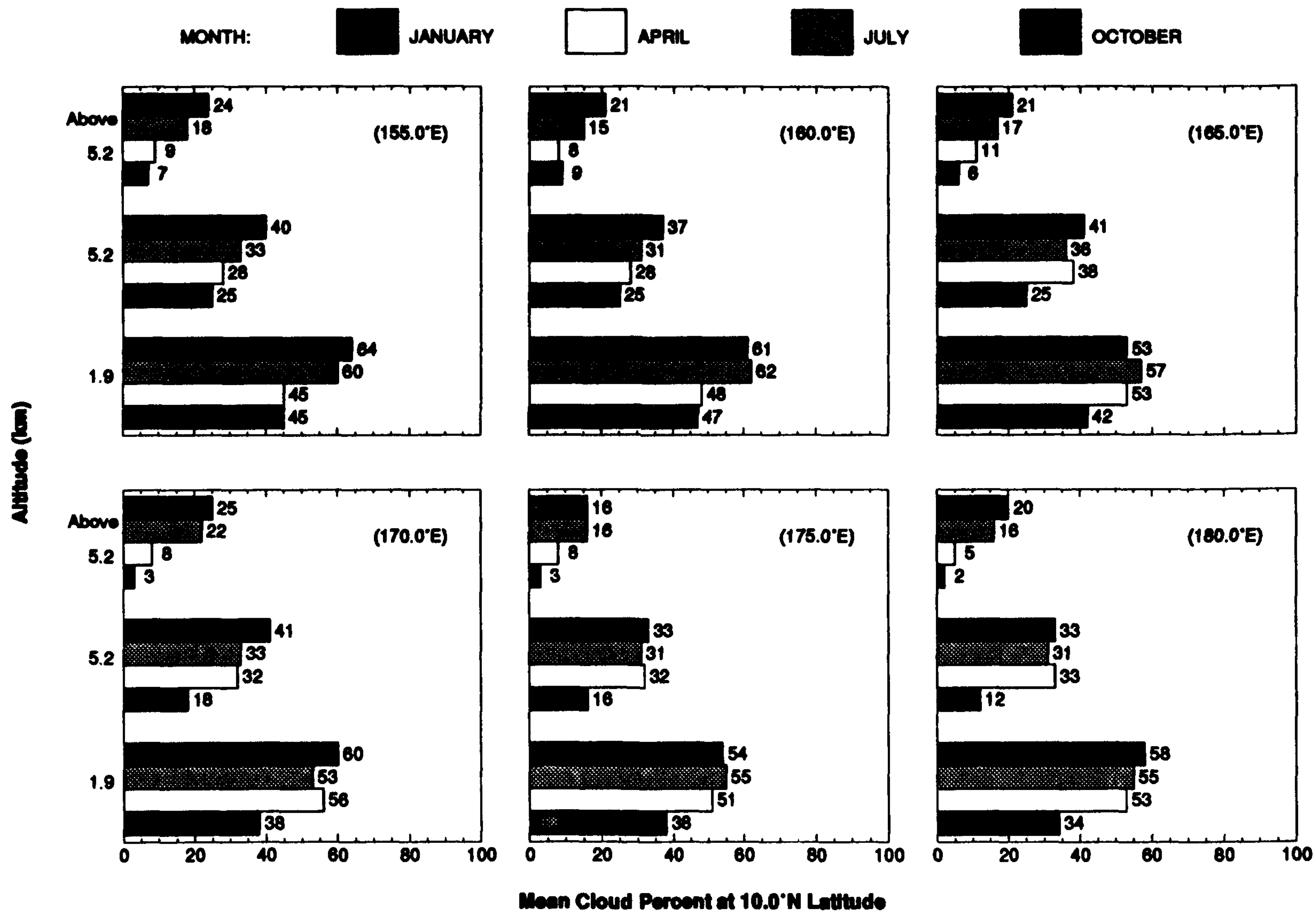


Mean Cloud Amount (in Percent) for Low (Surface - 1.9 km), Middle (1.9 - 5.2 km), and High (above 5.2 km) Clouds

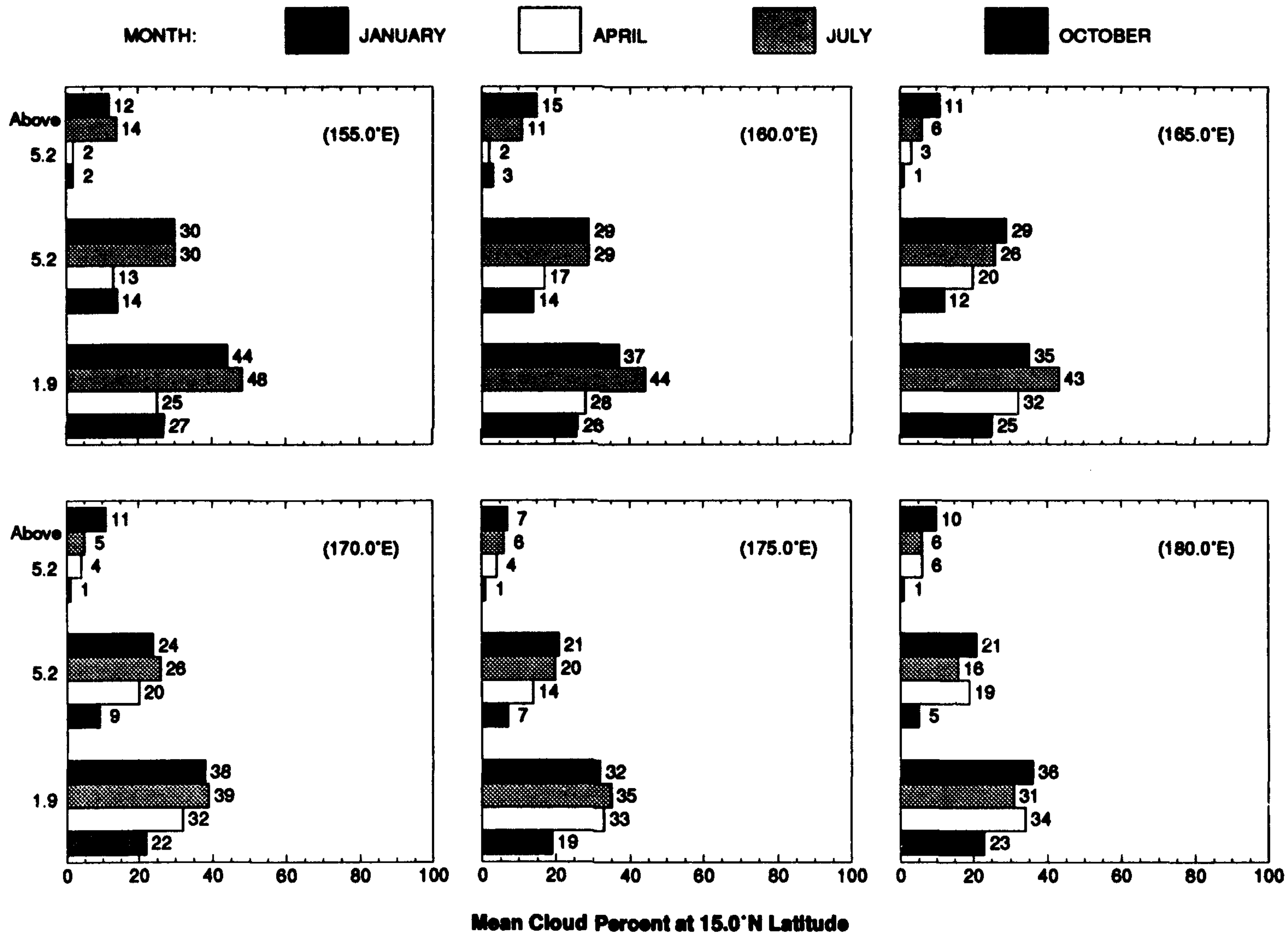
MONTH: JANUARY APRIL JULY OCTOBER



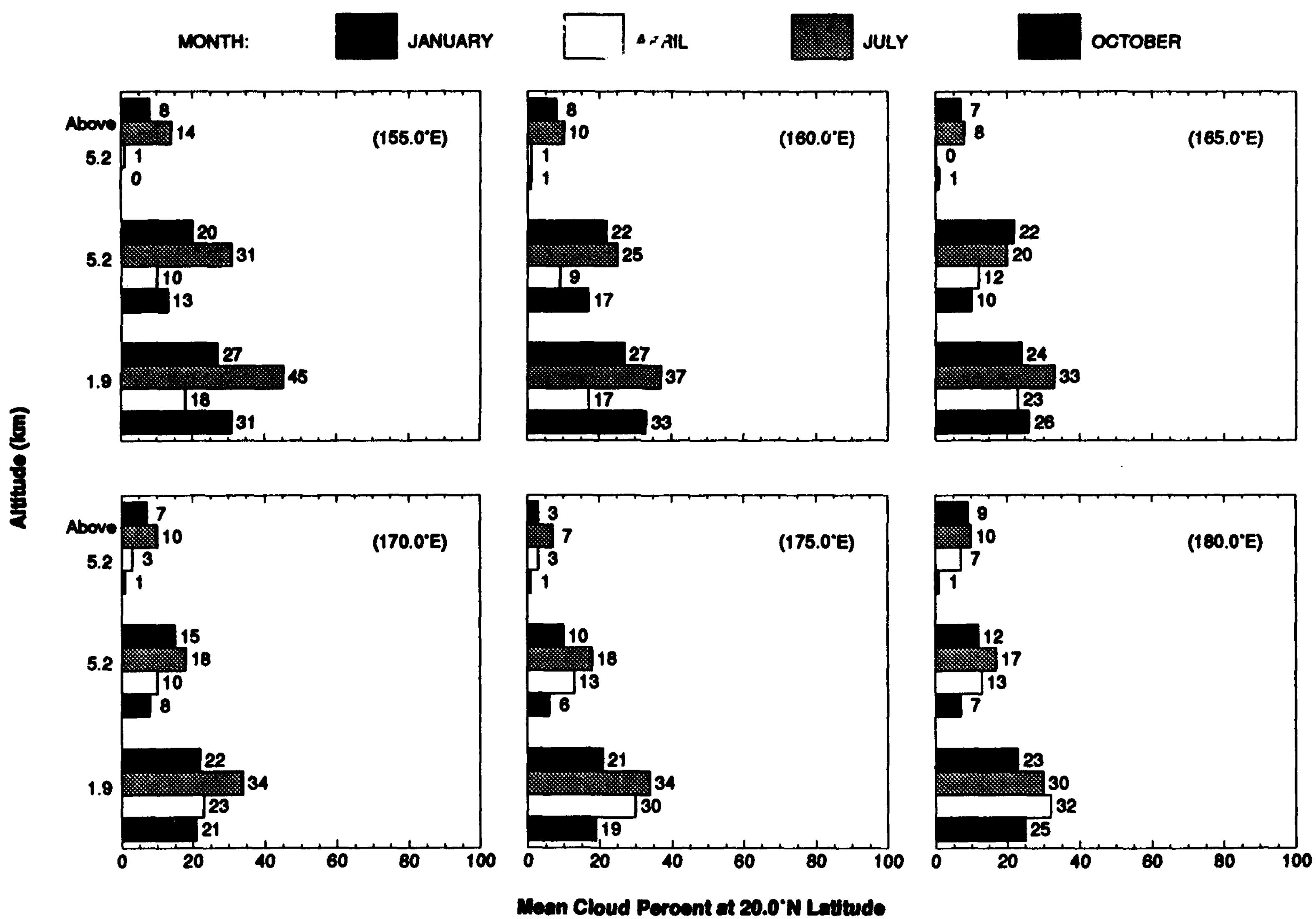
Mean Cloud Amount (in Percent) for Low (Surface - 1.9 km), Middle (1.9 - 5.2 km), and High (above 5.2 km) Clouds



Mean Cloud Amount (In Percent) for Low (Surface - 1.9 km), Middle (1.9 - 5.2 km), and High (above 5.2 km) Clouds



Mean Cloud Amount (in Percent) for Low (Surface - 1.9 km), Middle (1.9 - 5.2 km), and High (above 5.2 km) Clouds

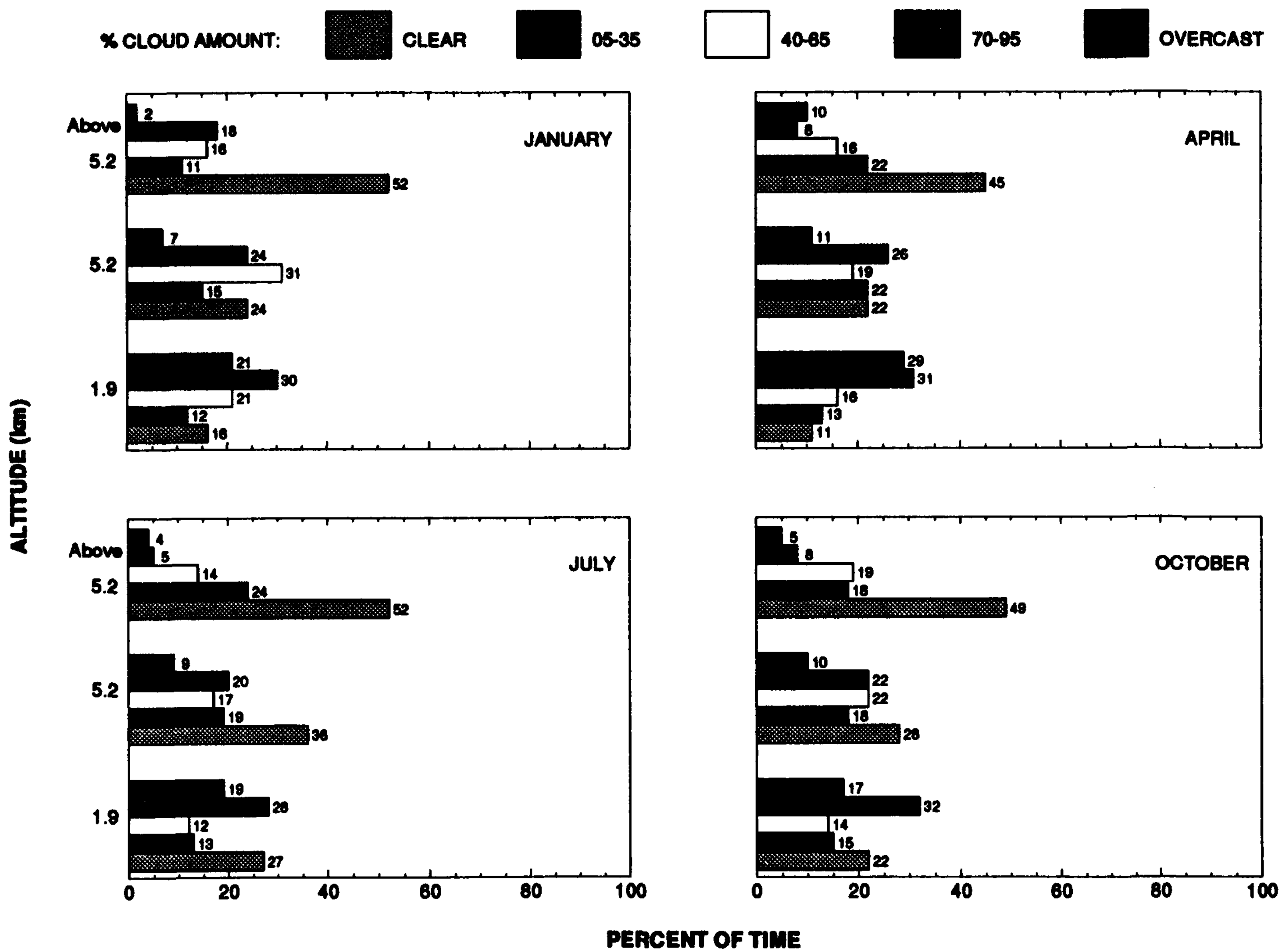


APPENDIX B

CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(0.0°N, 155.0°E)



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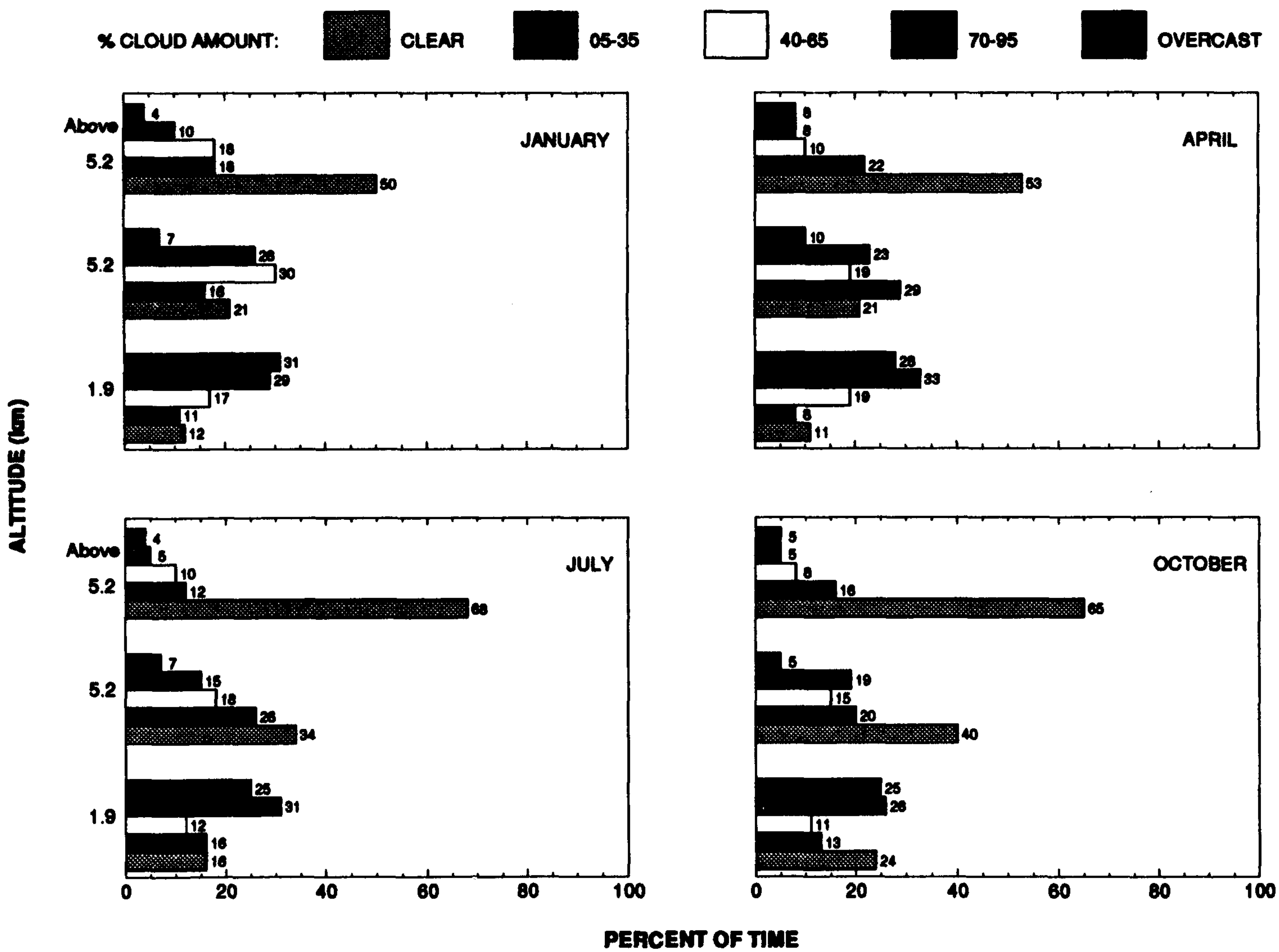
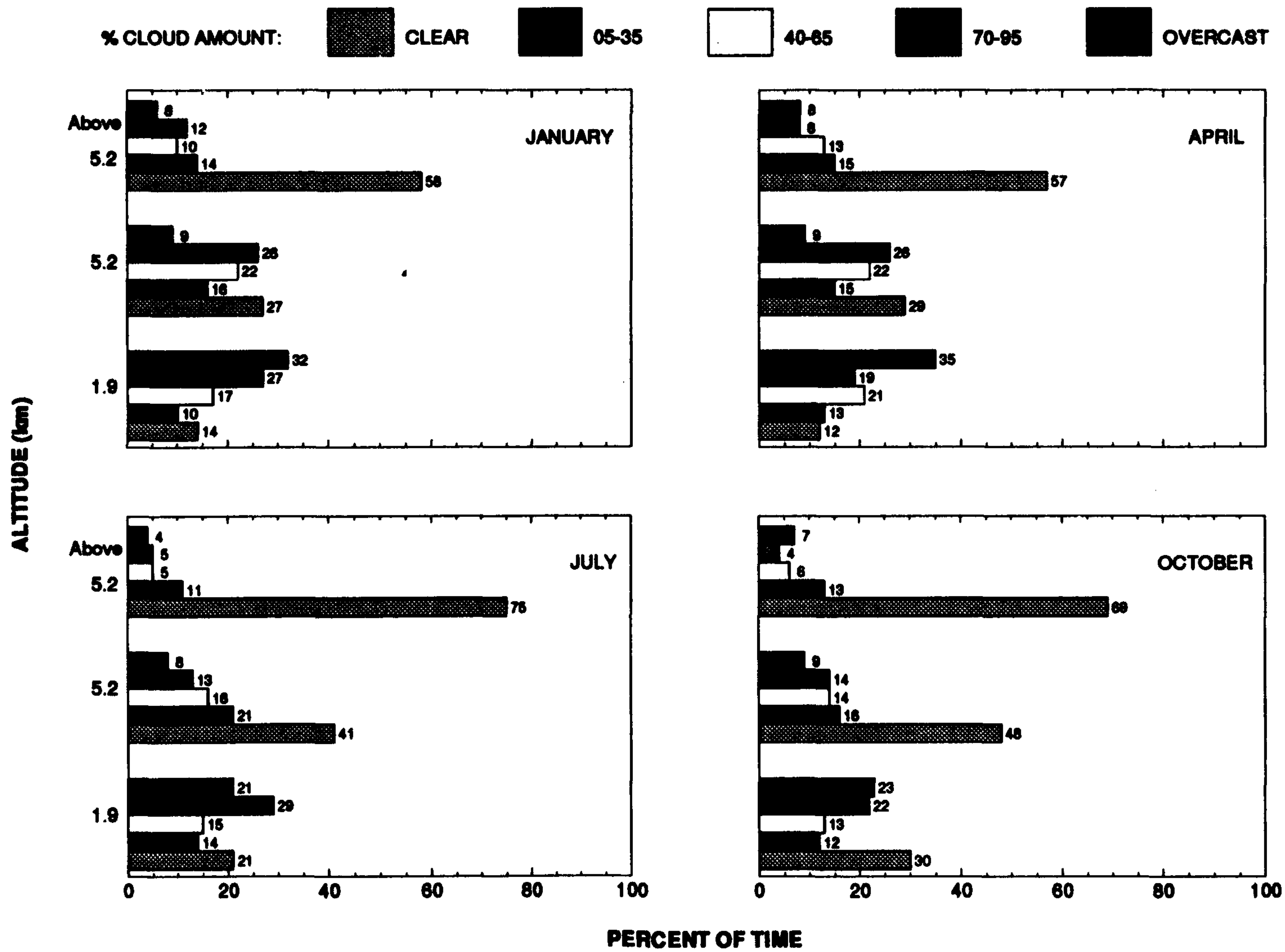


CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(0.0°N, 165.0°E)



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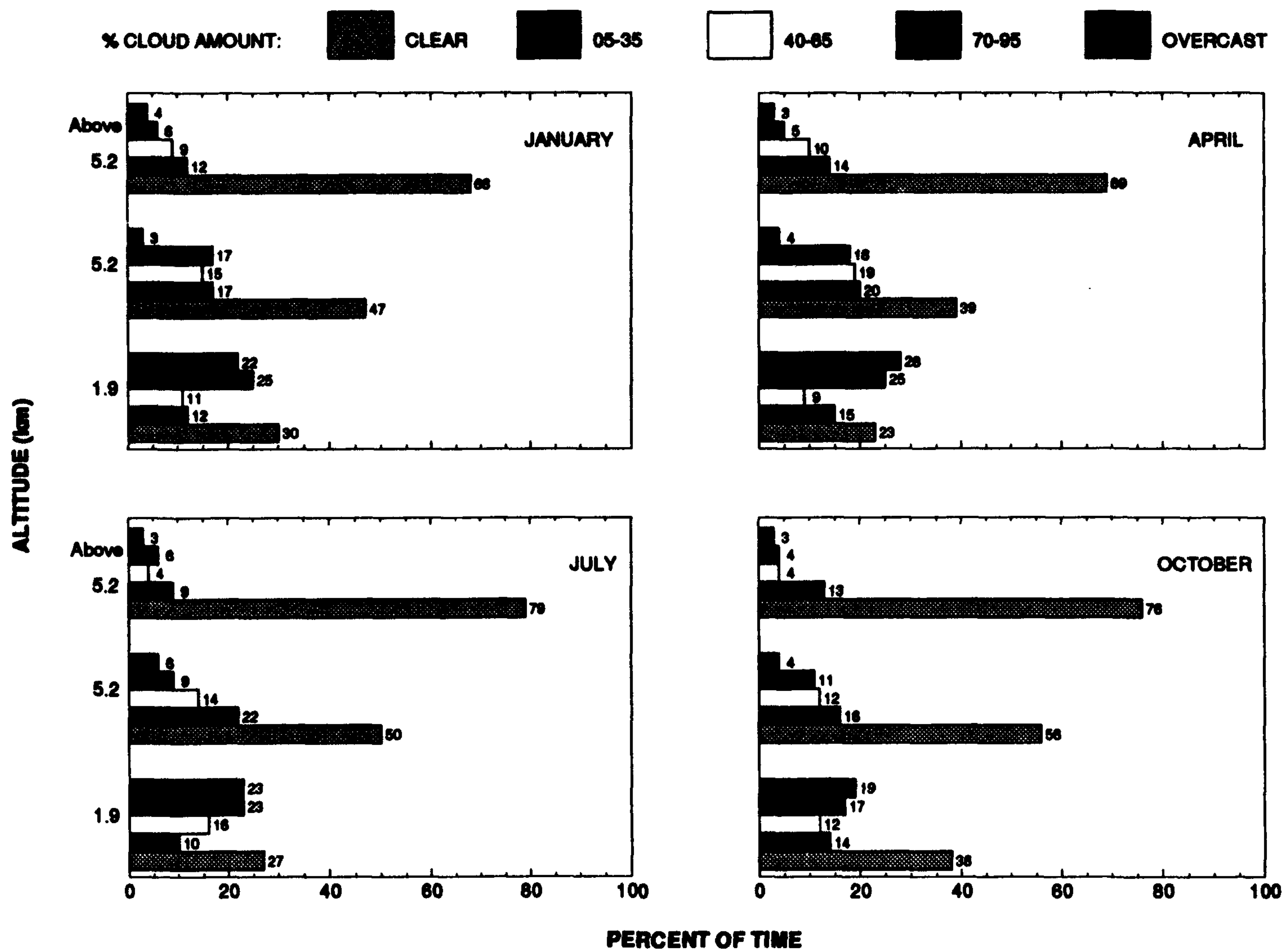
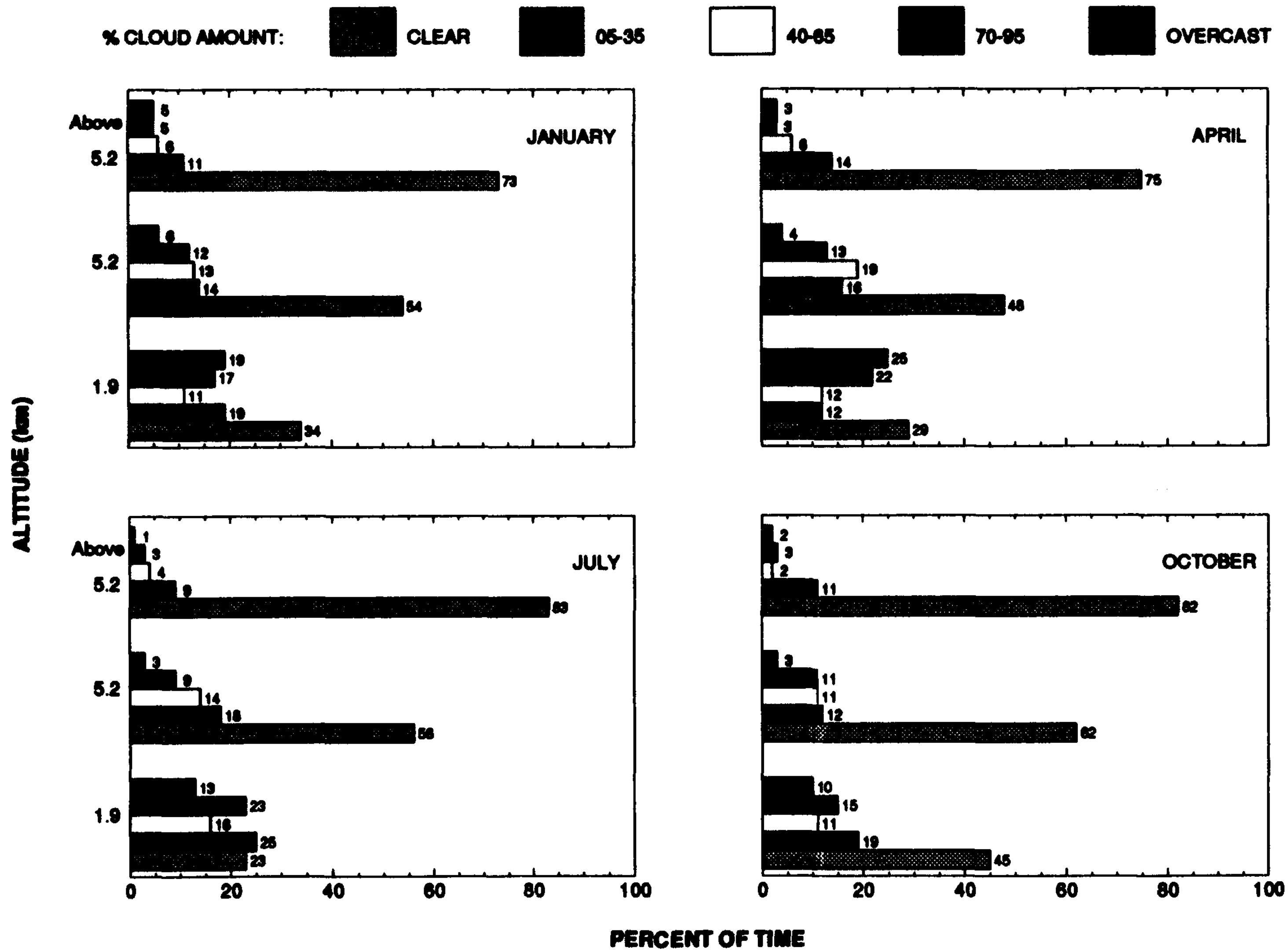


CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(0.0°N, 175.0°E)



CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

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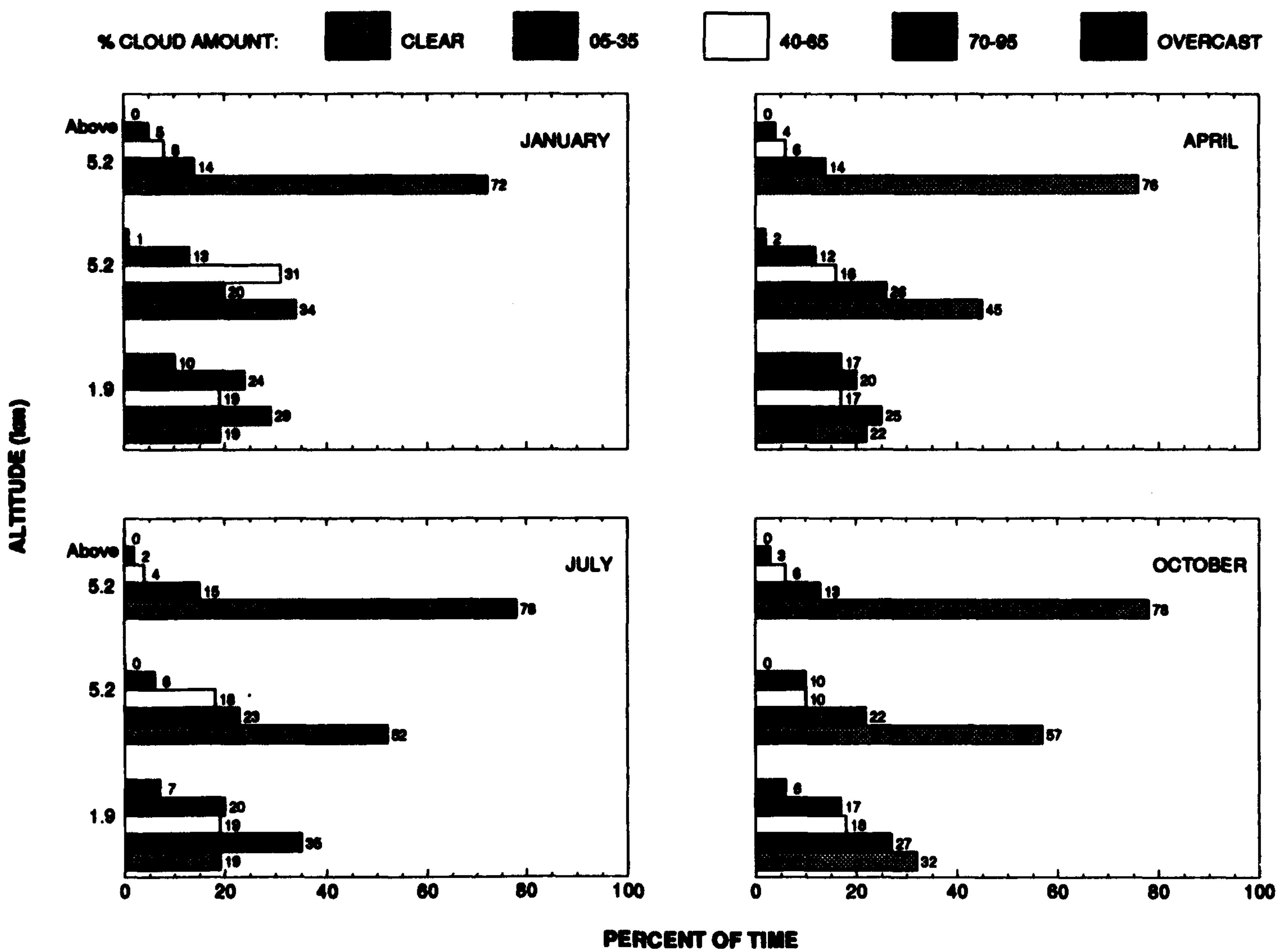
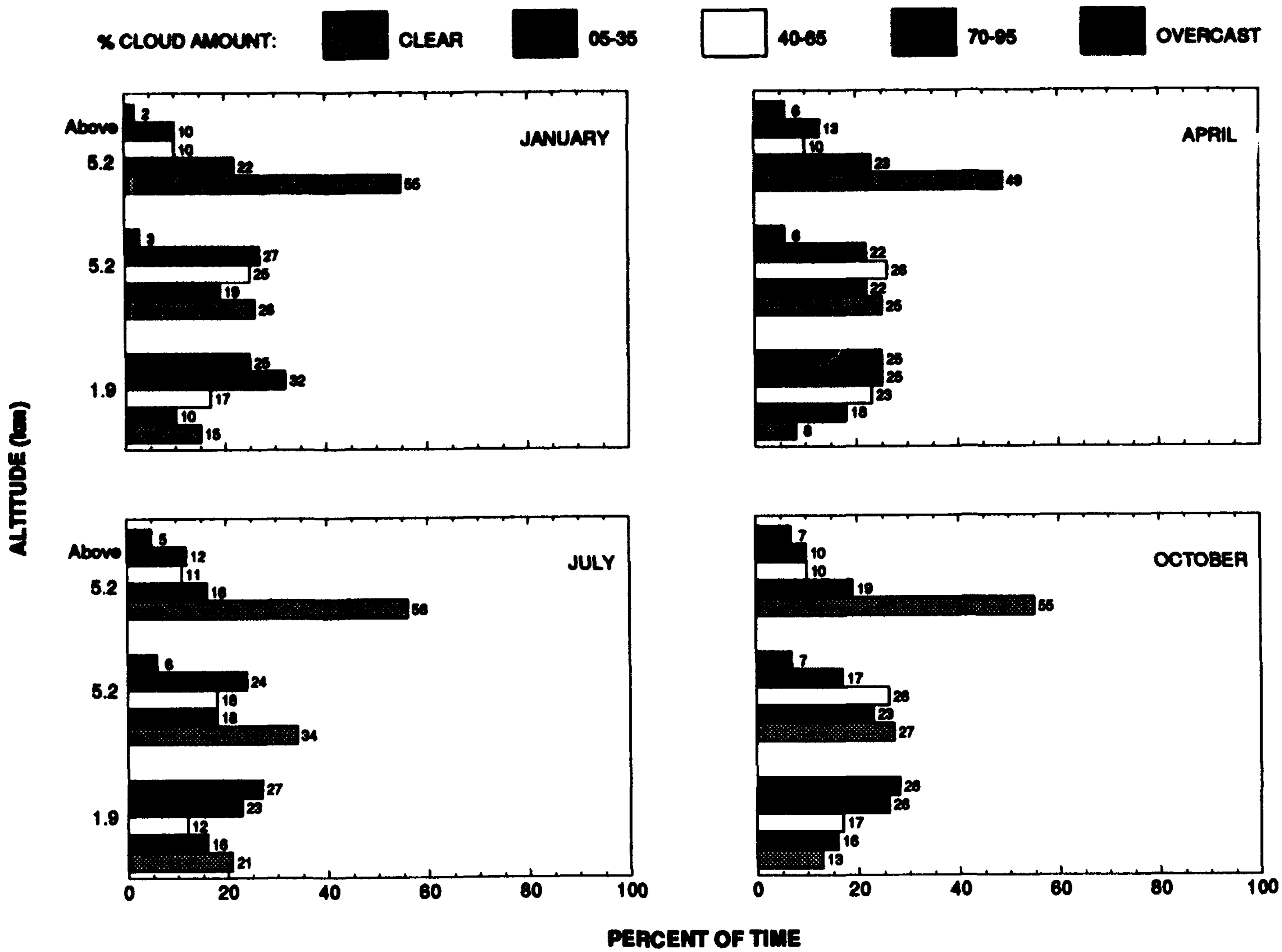


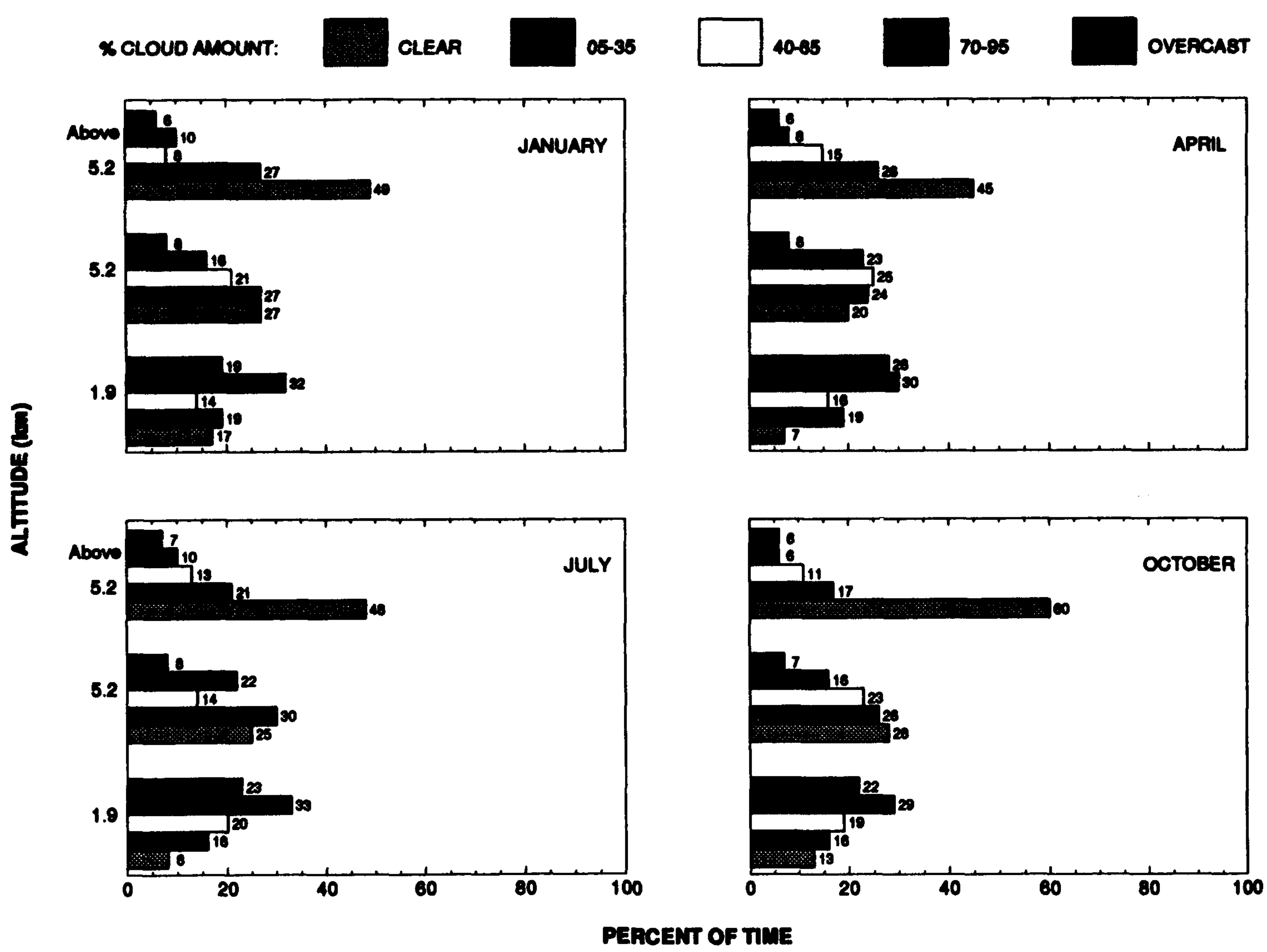
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(5.0°N, 155.0°E)



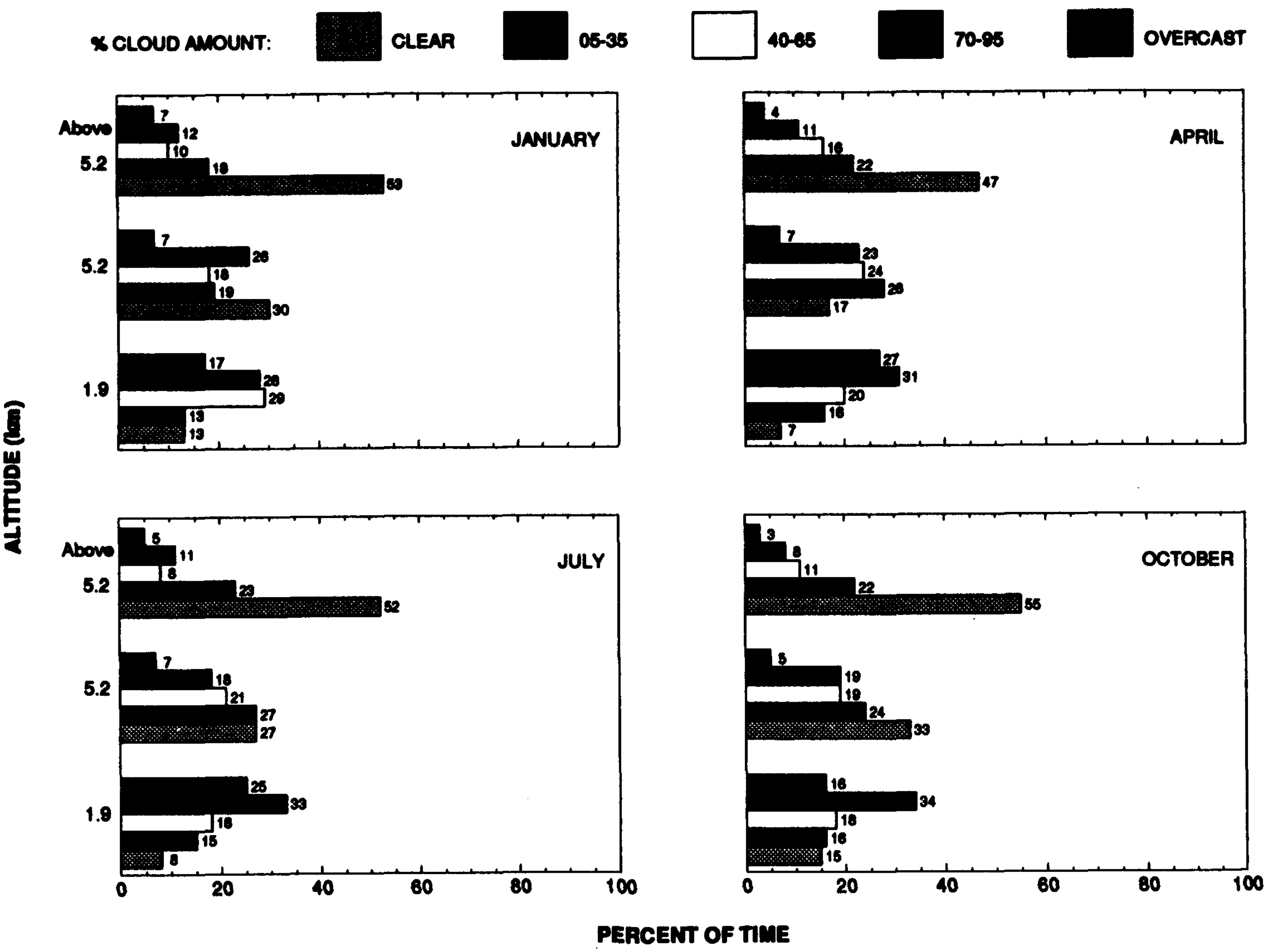
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(5.0°N, 160.0°E)



CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(5.0°N, 165.0°E)



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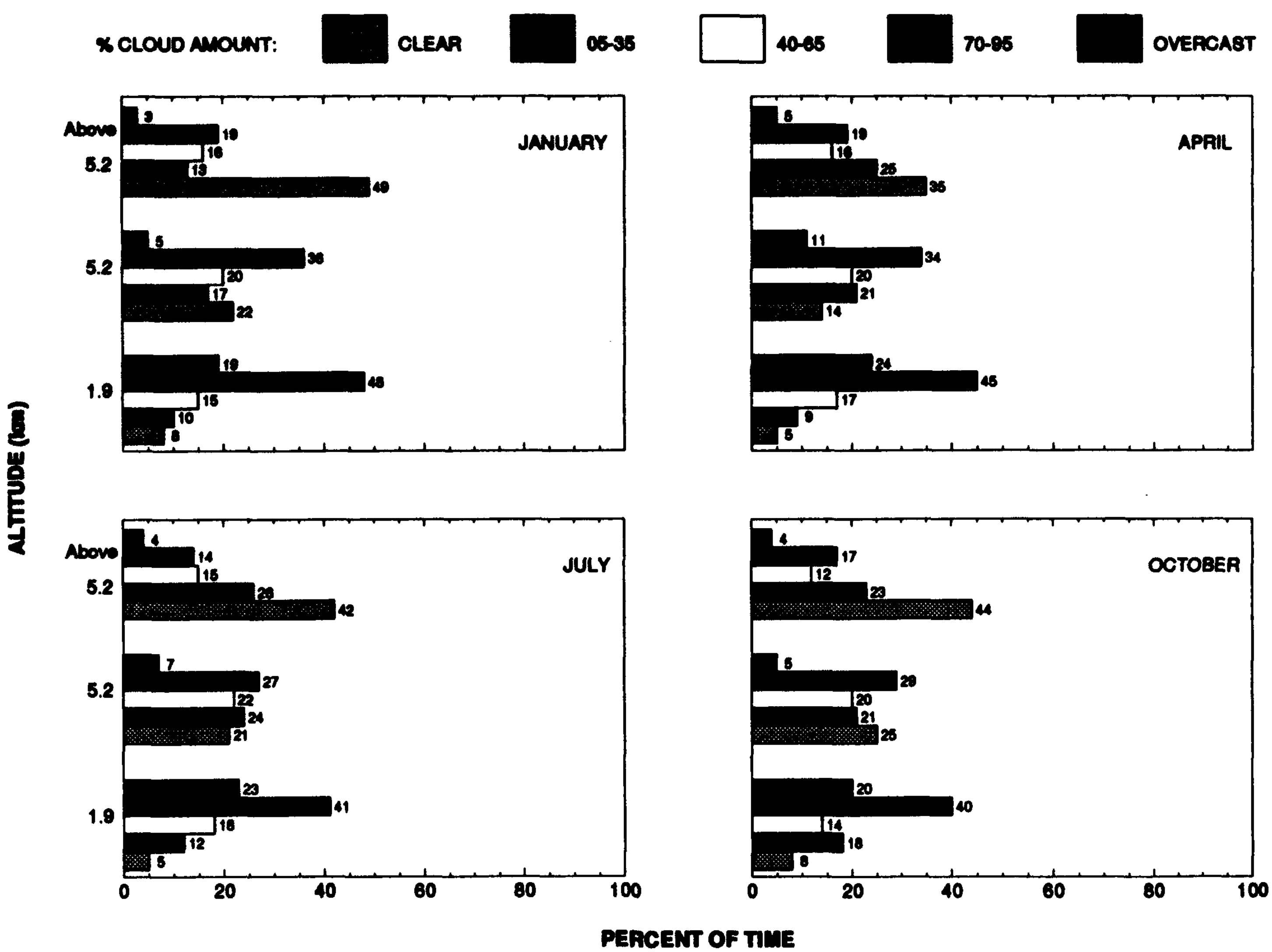
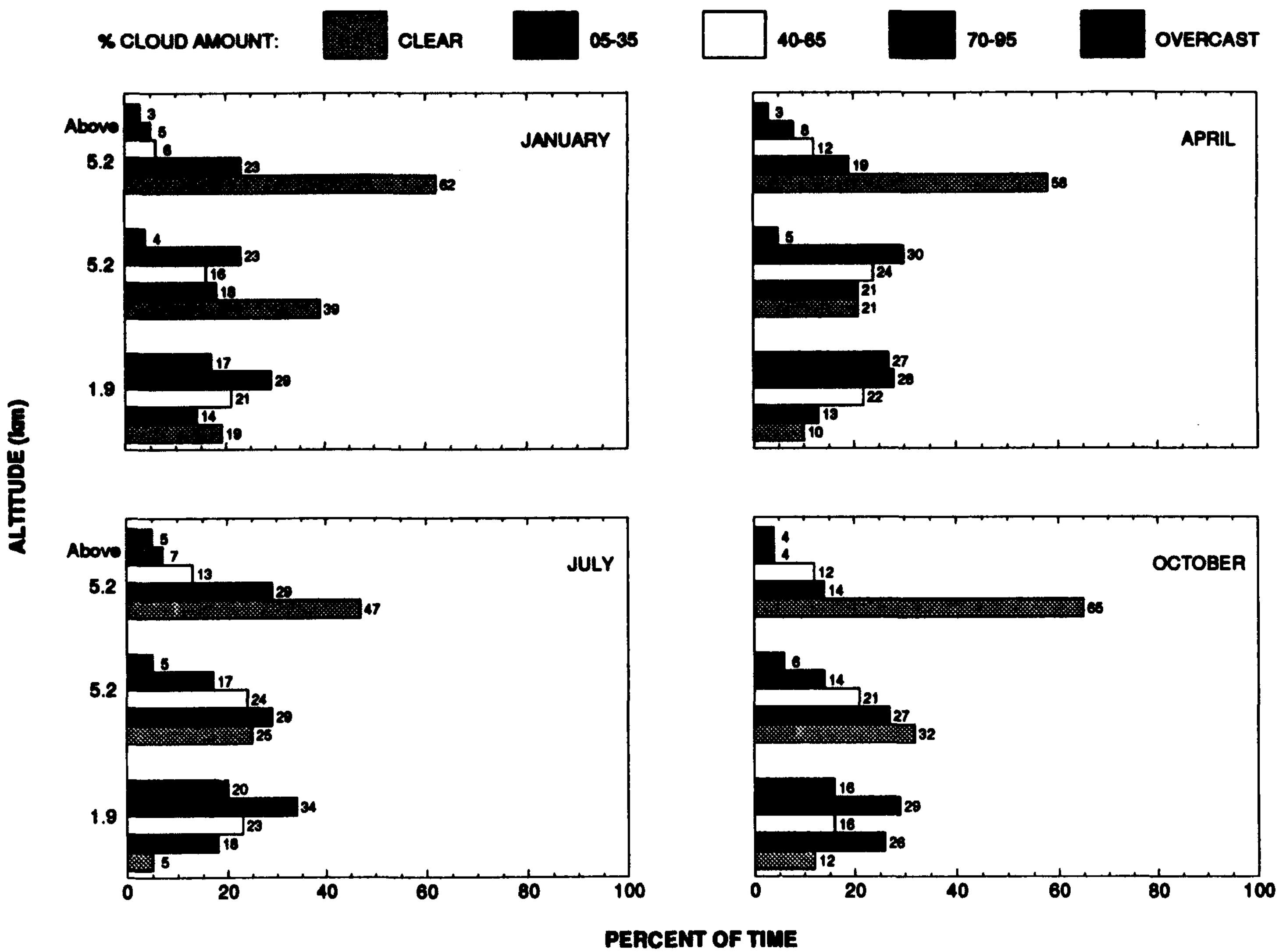
(5.0°N, 170.0°E)



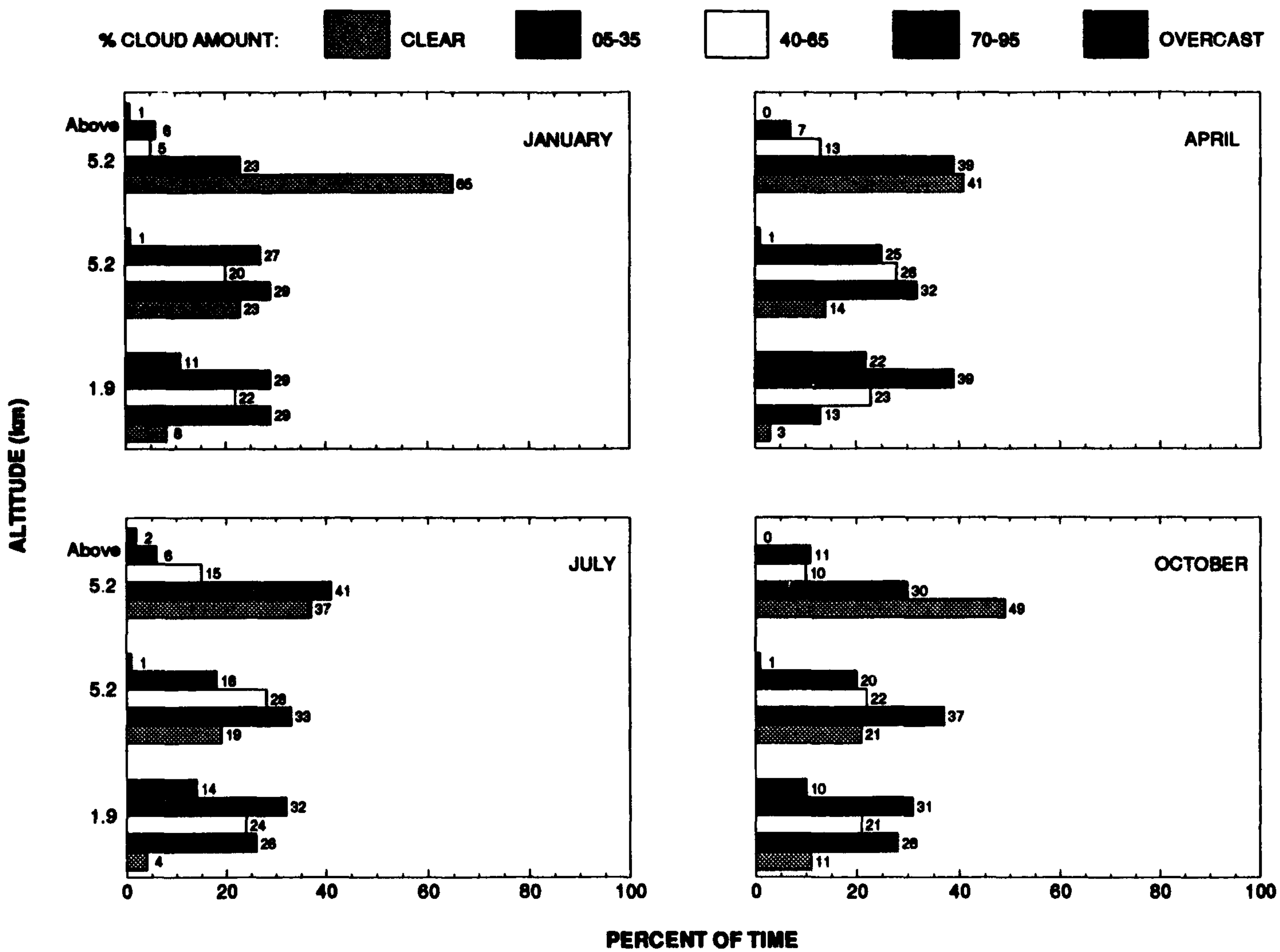
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(5.0°N, 175.0°E)



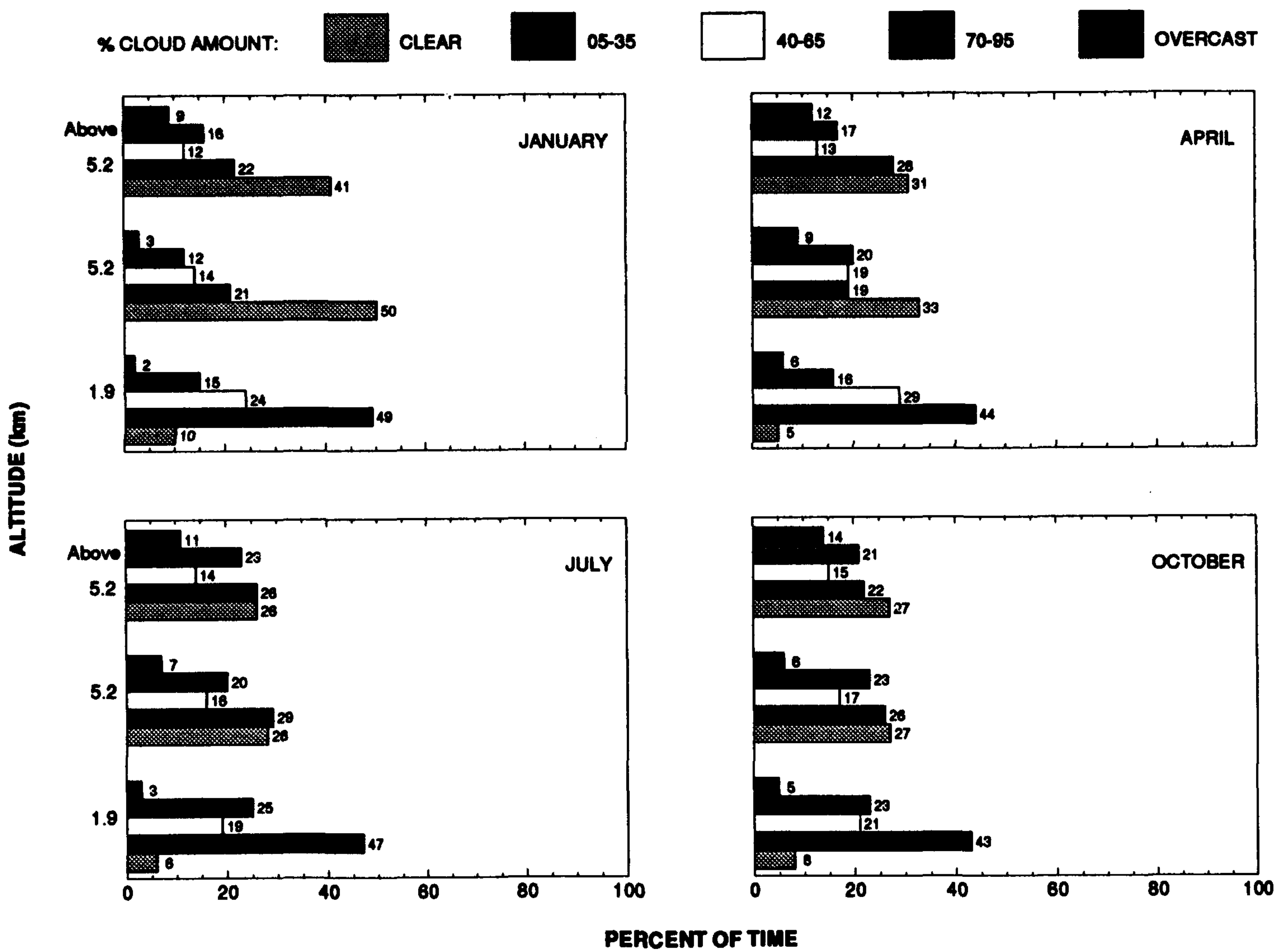
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(5.0°N, 180.0°E)



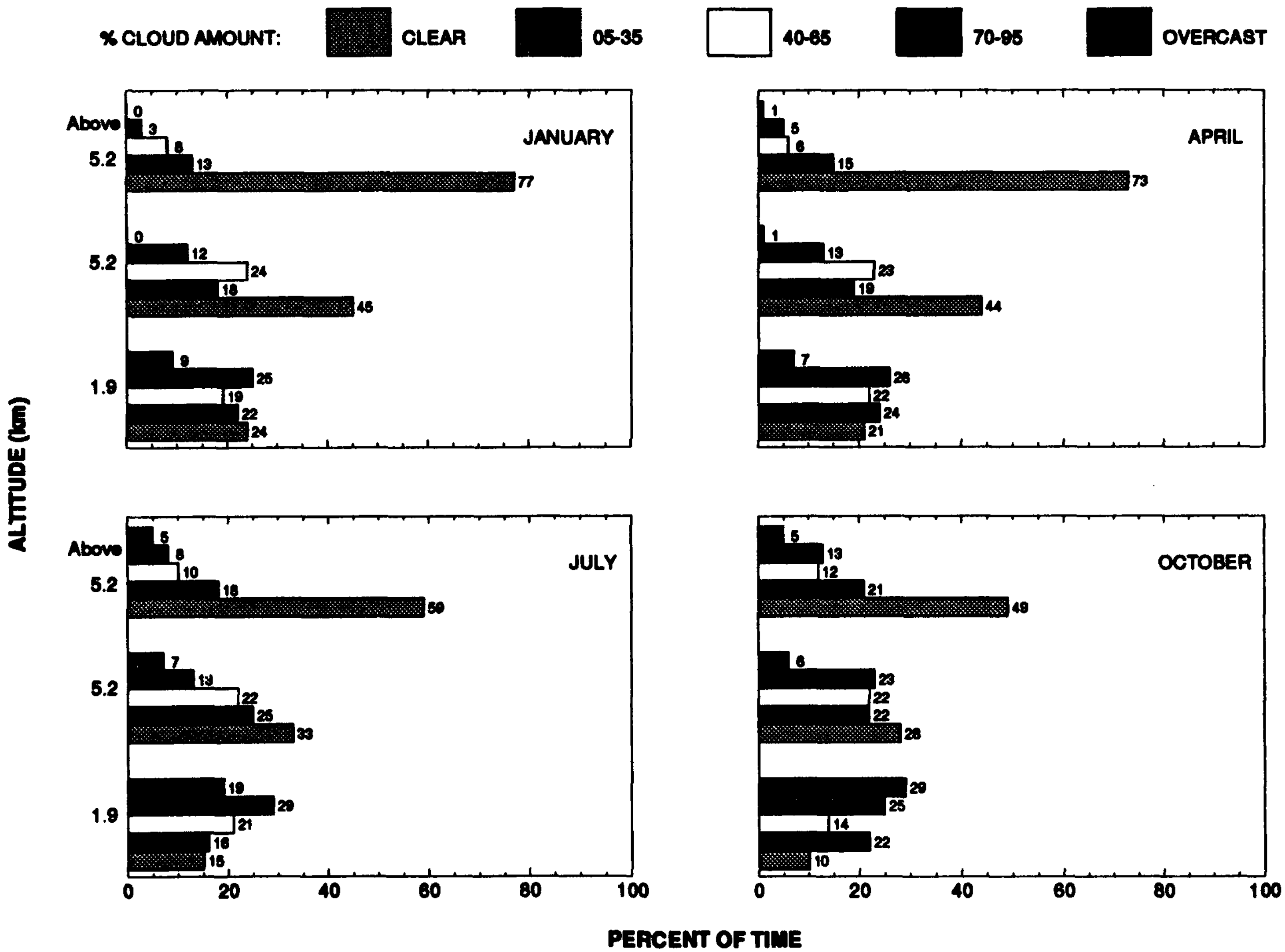
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

KWAJALEIN (9.4°N, 167.5°E)



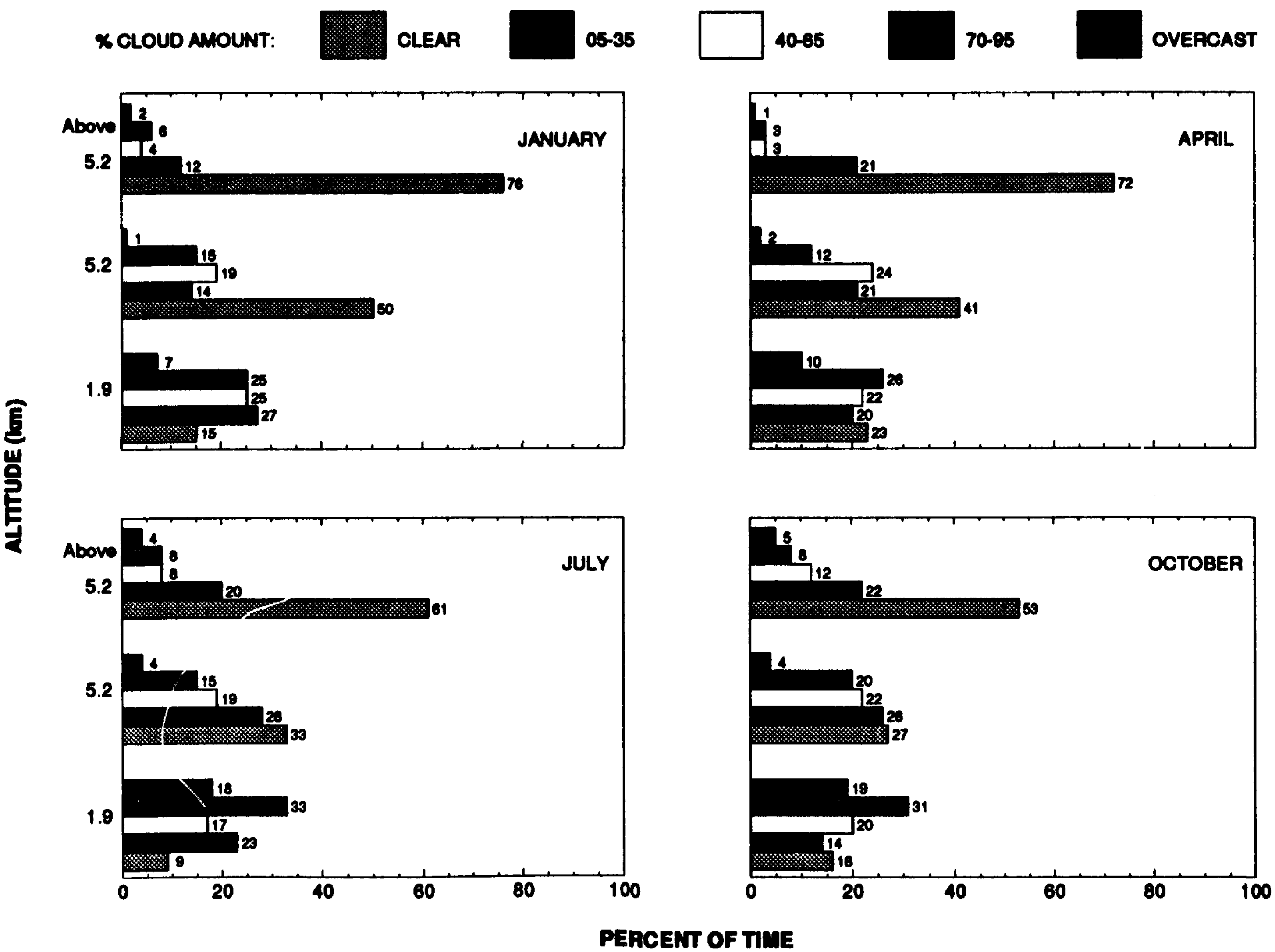
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(10.0°N, 155.0°E)



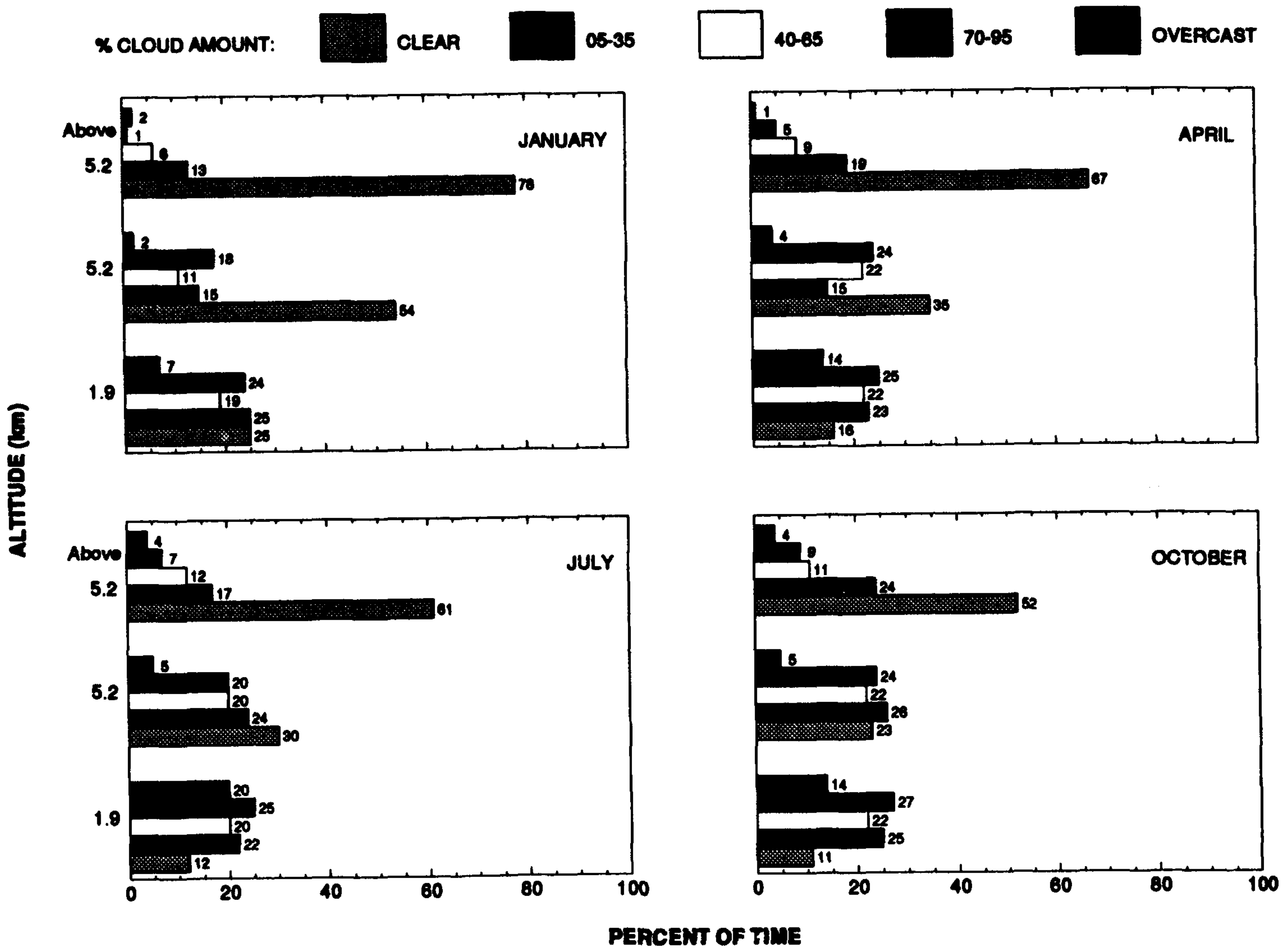
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(10.0°N, 160.0°E)



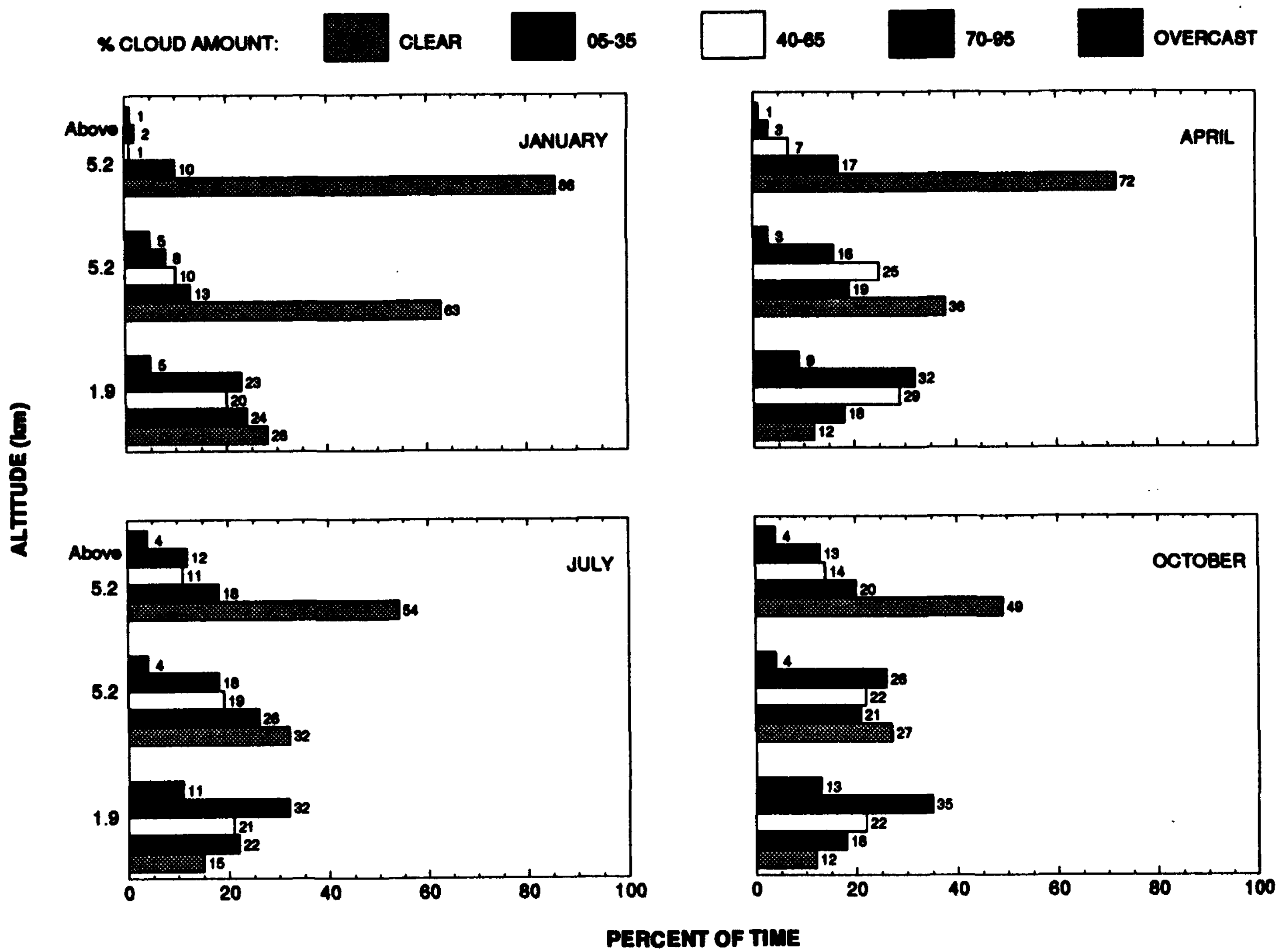
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

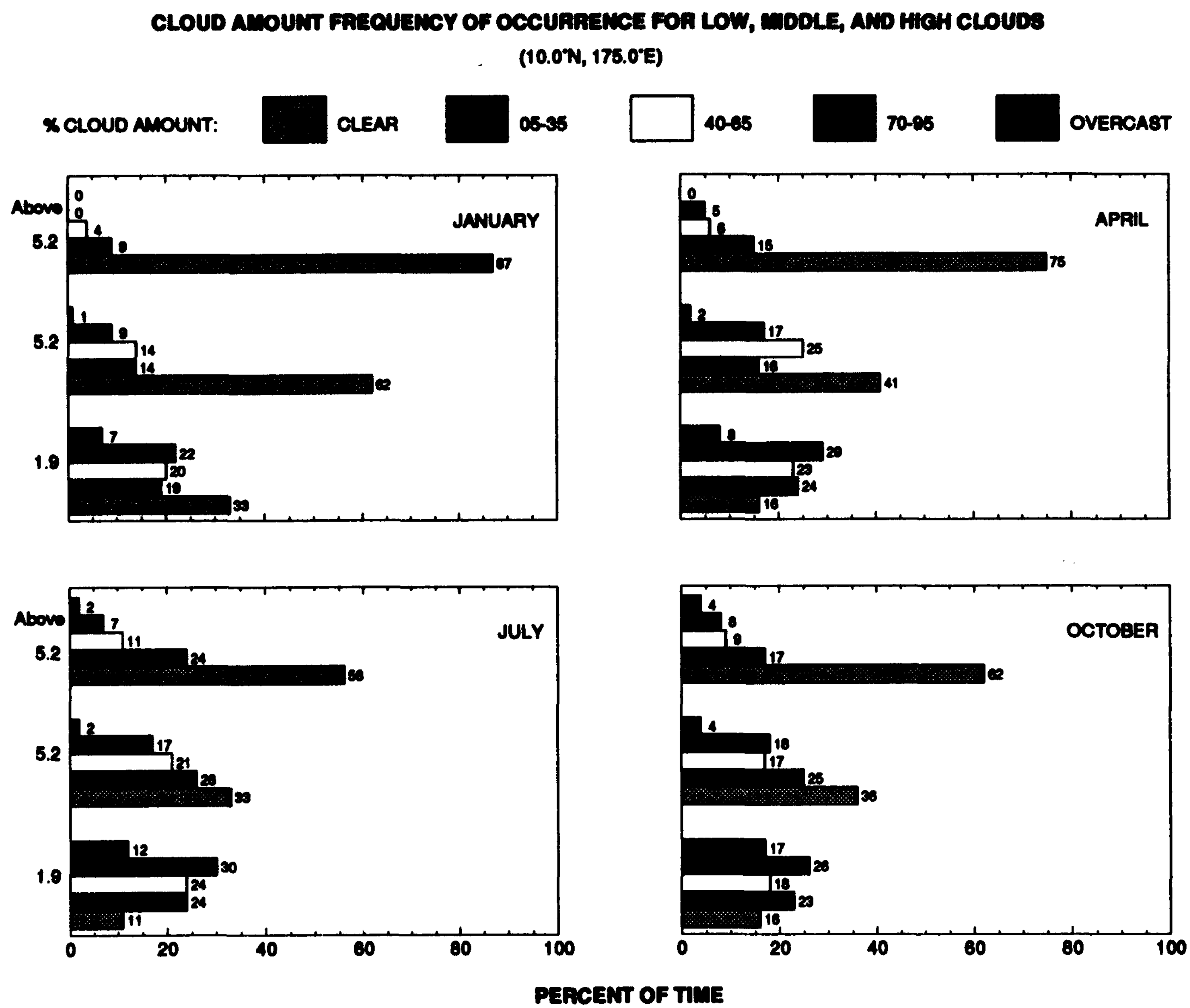
(10.0°N, 165.0°E)



CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

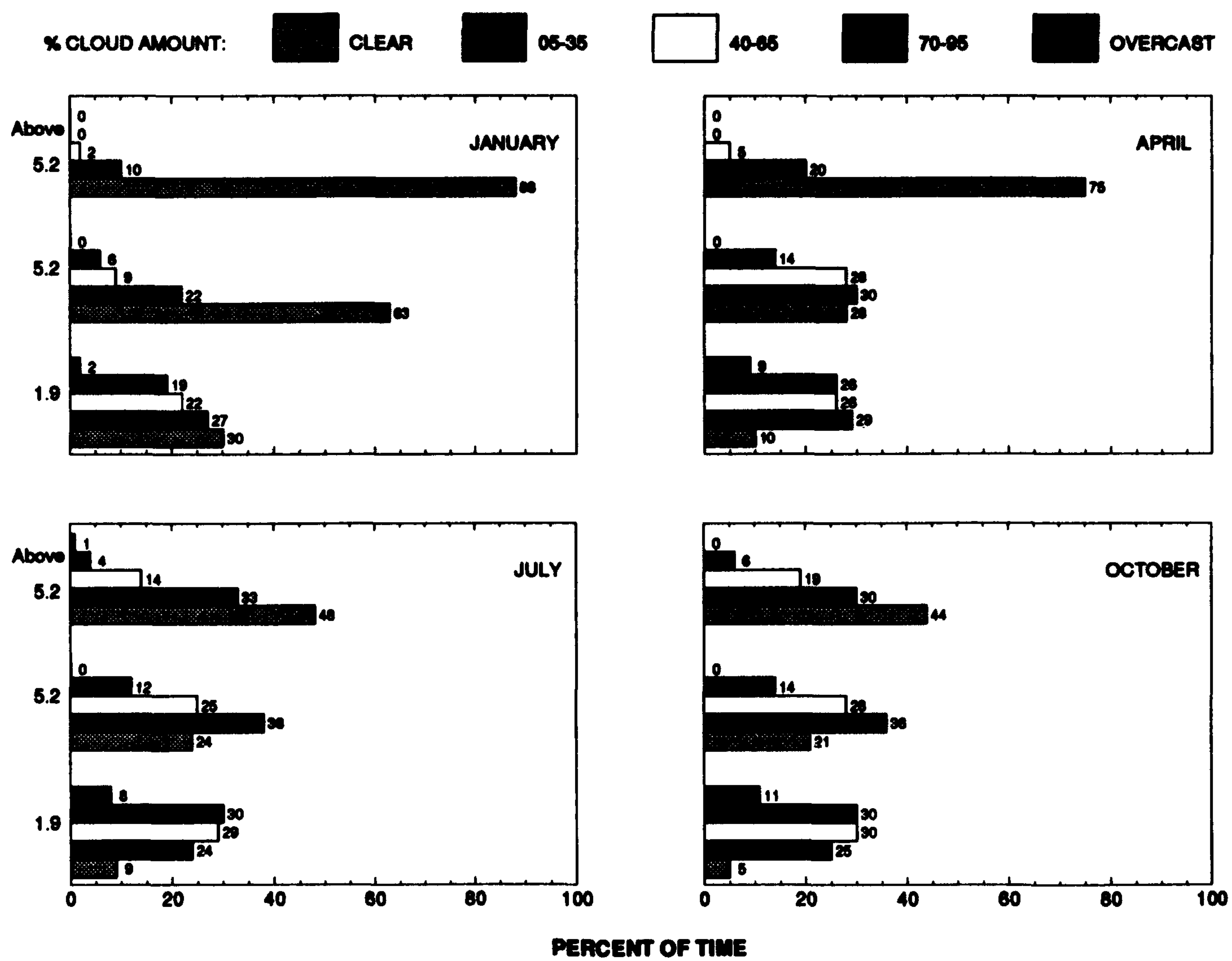
(10.0°N, 170.0°E)




CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS
(10.0°N, 175.0°E)
% CLOUD AMOUNT:
CLEAR
05-35
40-65
70-95
OVERCAST
JANUARY
APRIL
JULY
OCTOBER
Above 5.2
5.2
1.9
ALTITUDE (km)
PERCENT OF TIME
0
20
40
60
80
100

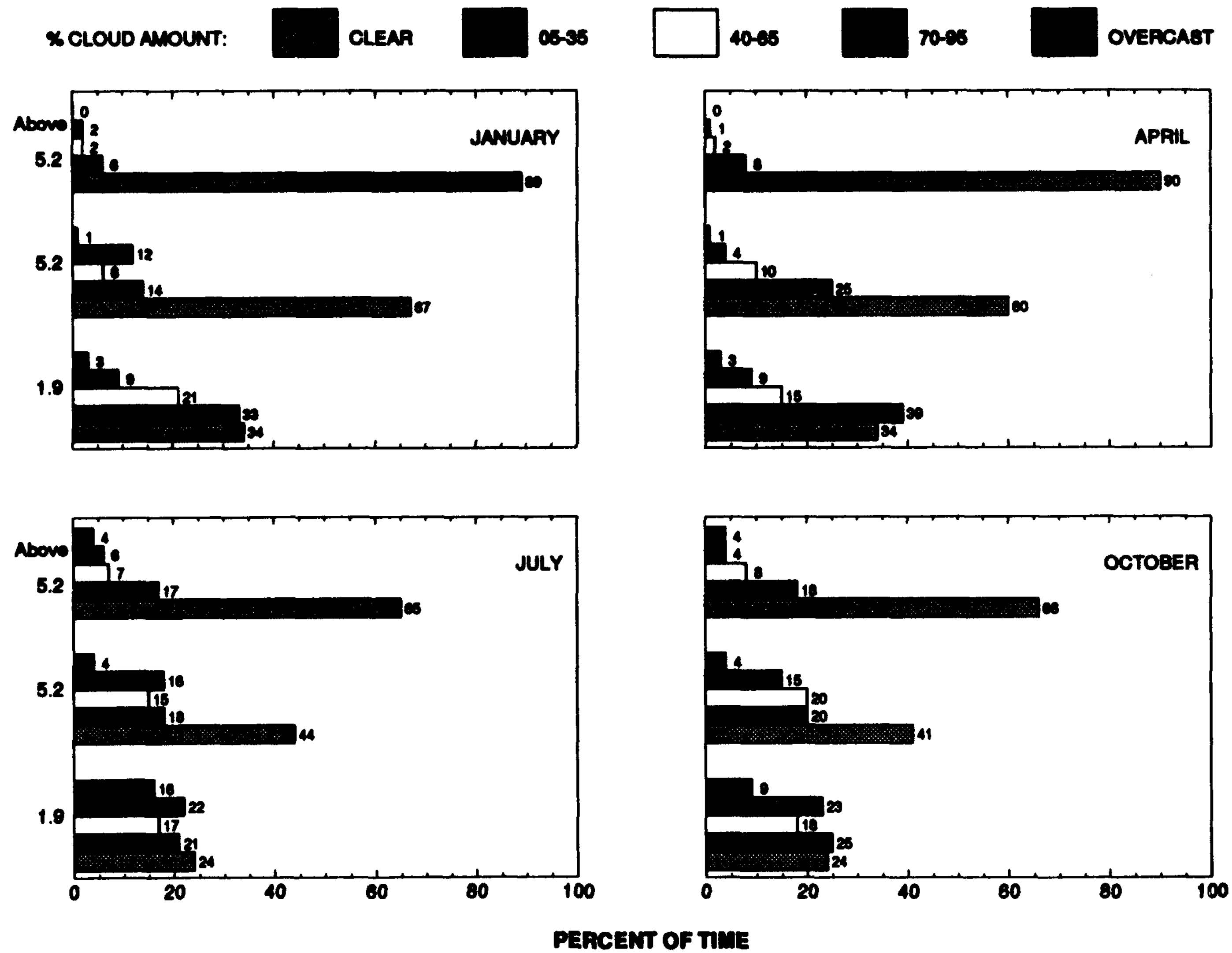
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(10.0°N, 180.0°E)



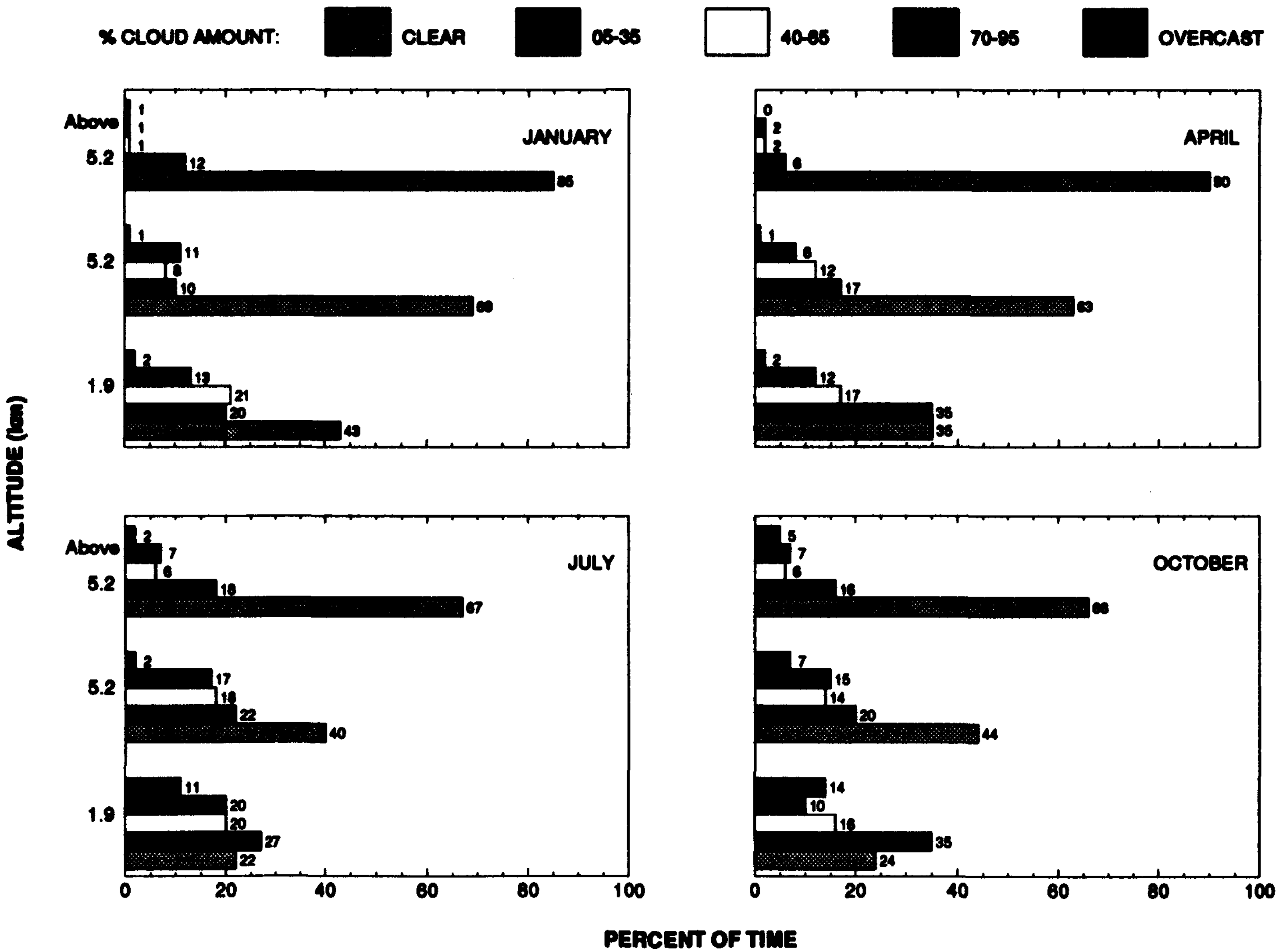
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(15.0°N, 155.0°E)



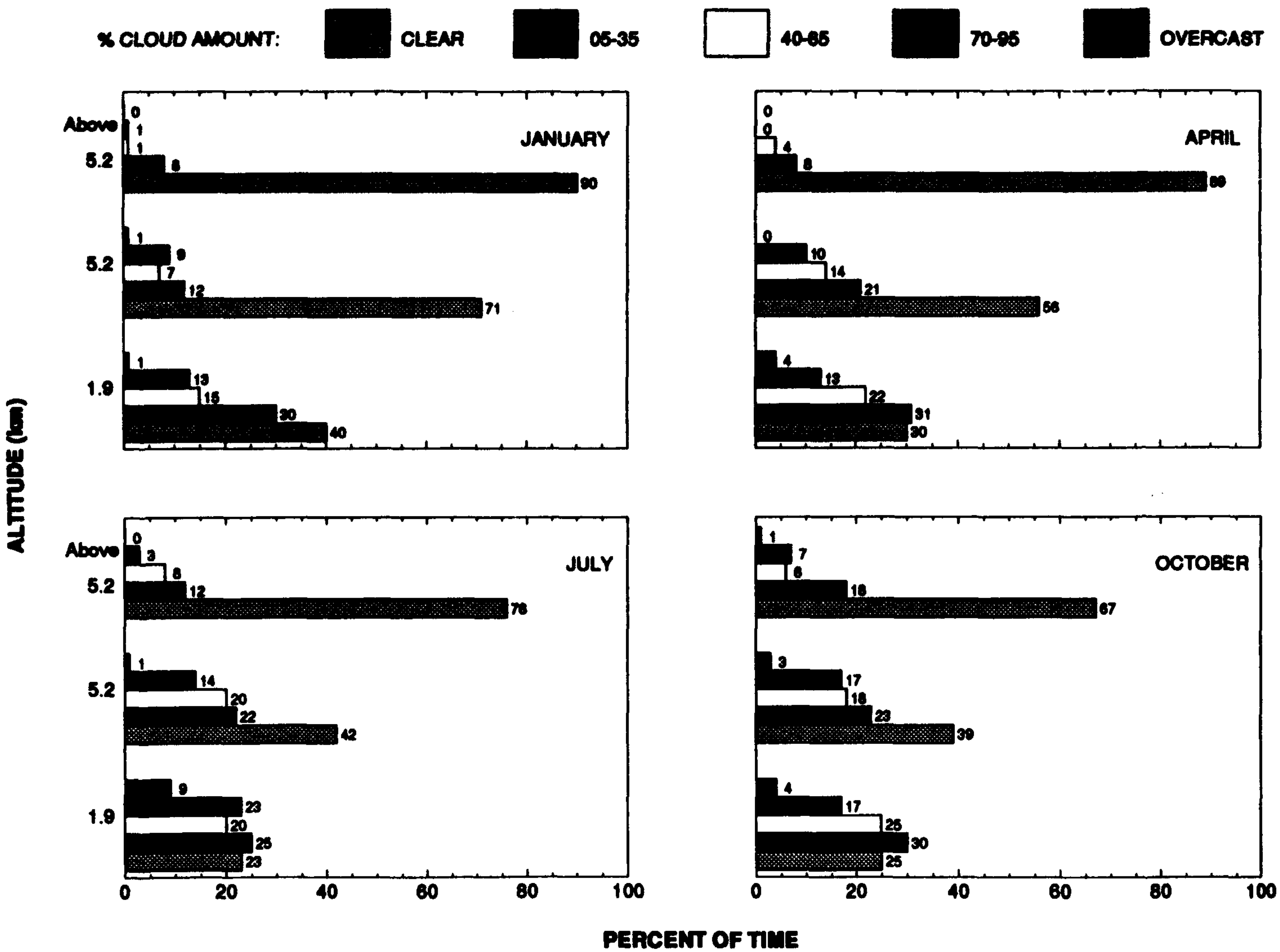
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(15.0°N, 160.0°E)



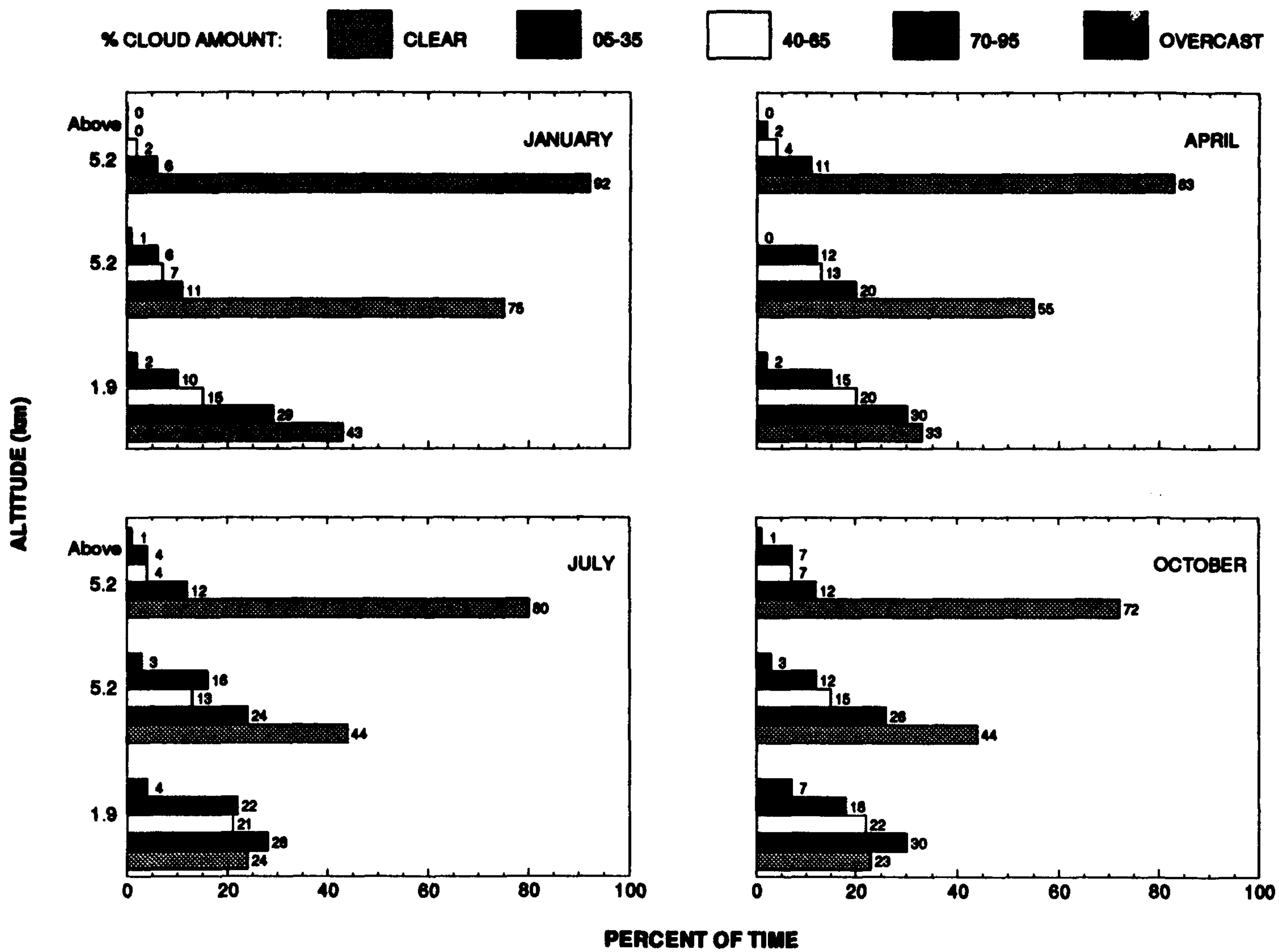
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(15.0°N, 165.0°E)



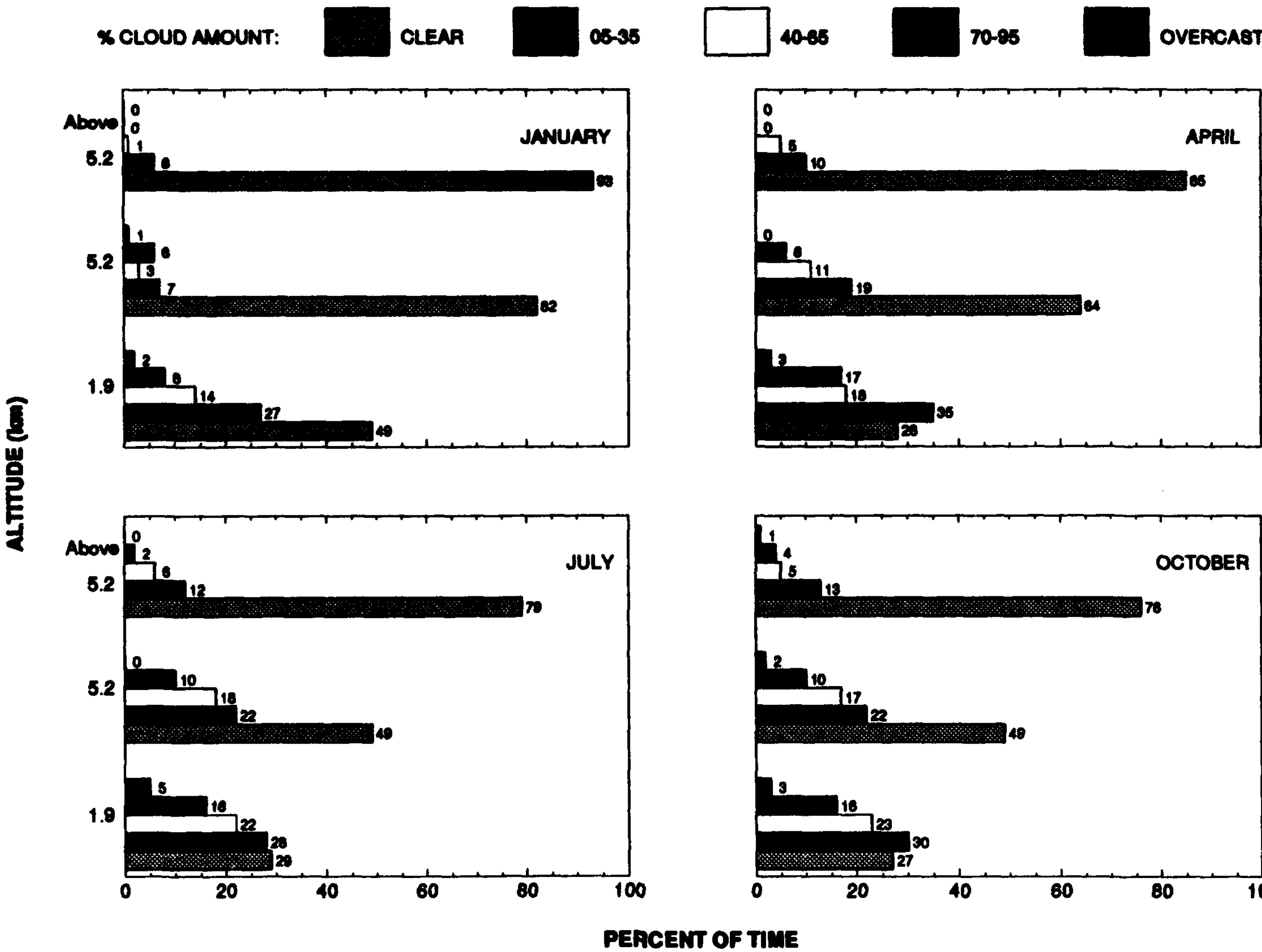
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(15.0°N, 170.0°E)



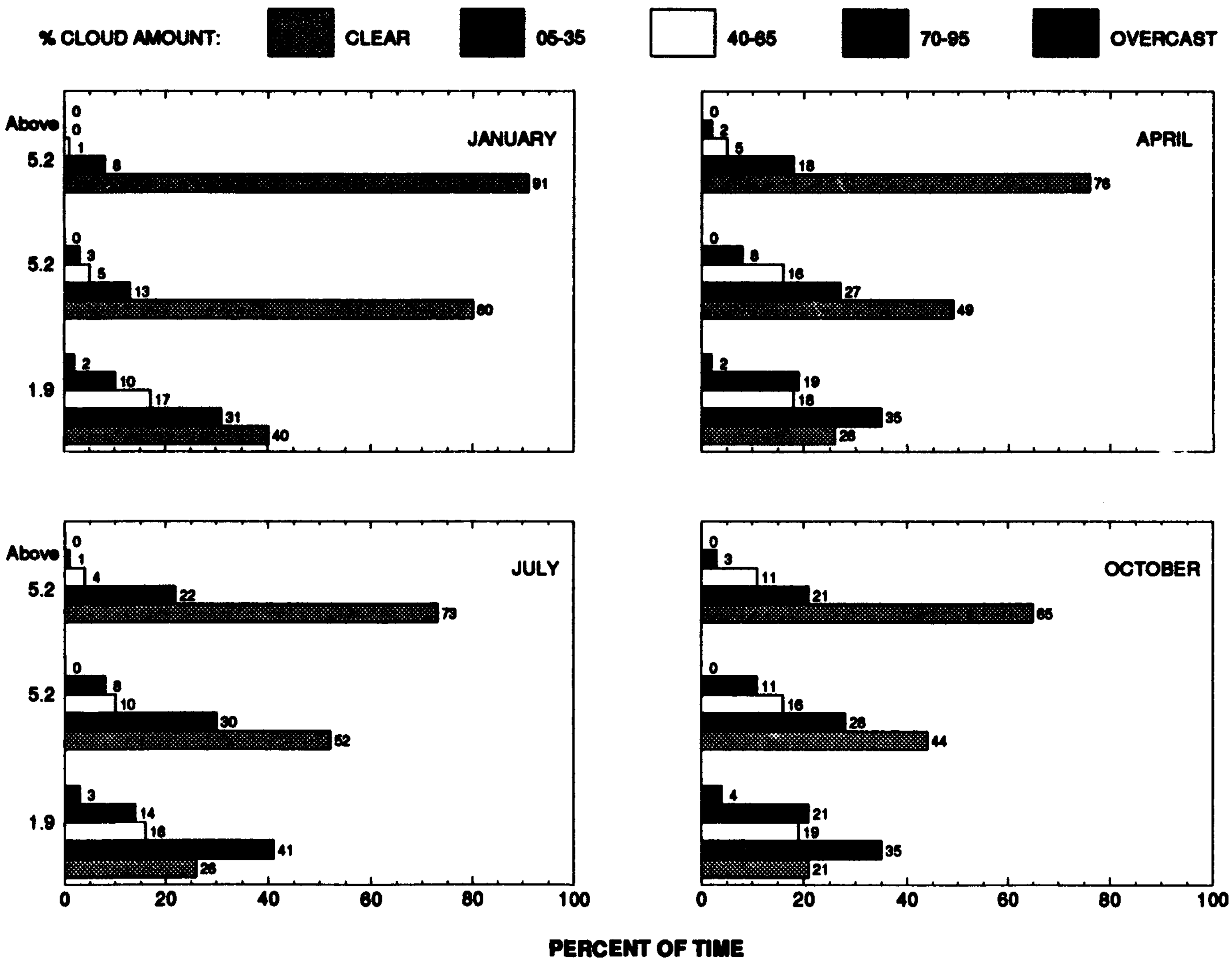
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(15.0°N, 175.0°E)



CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(15.0°N, 180.0°E)



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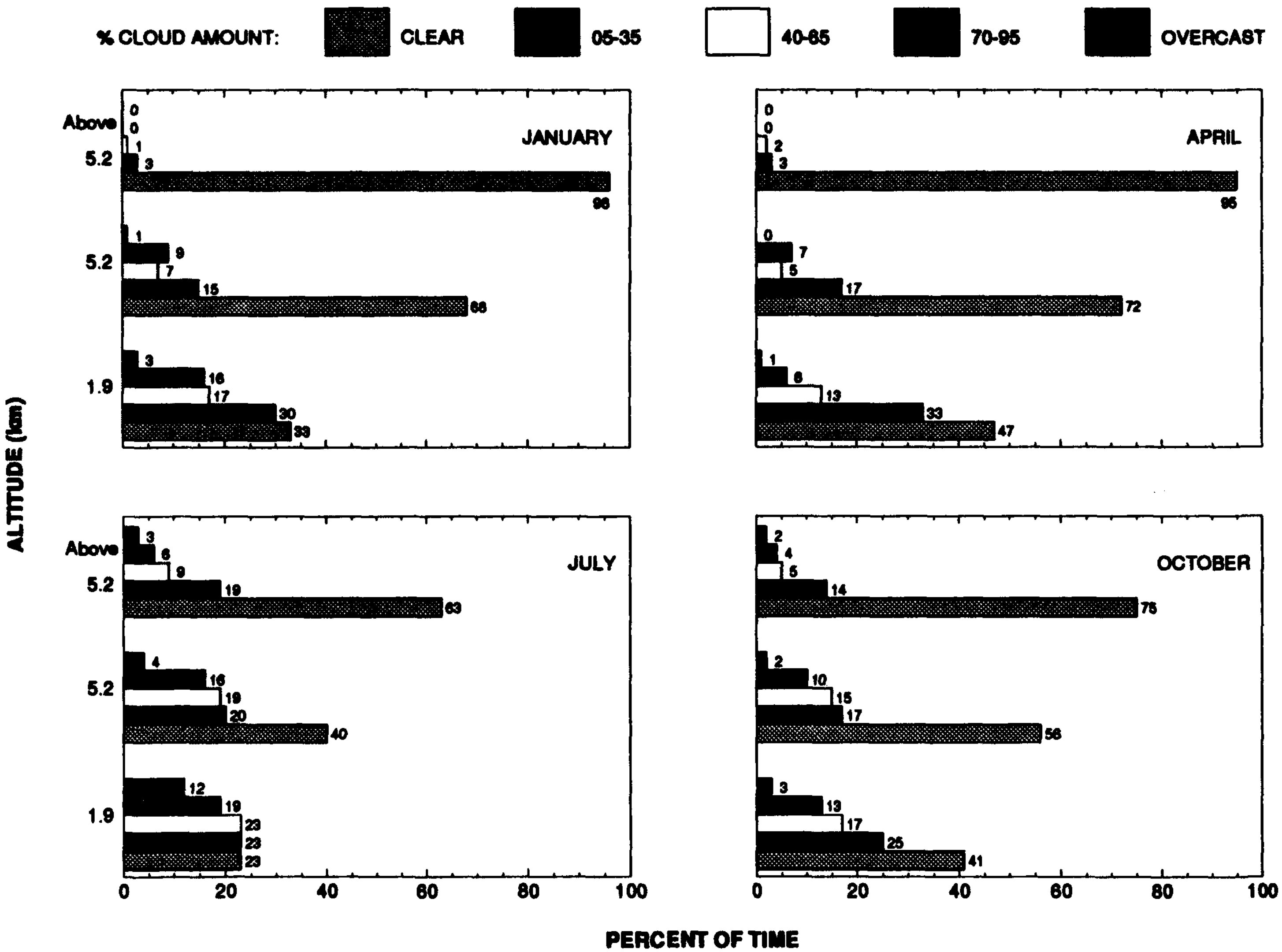
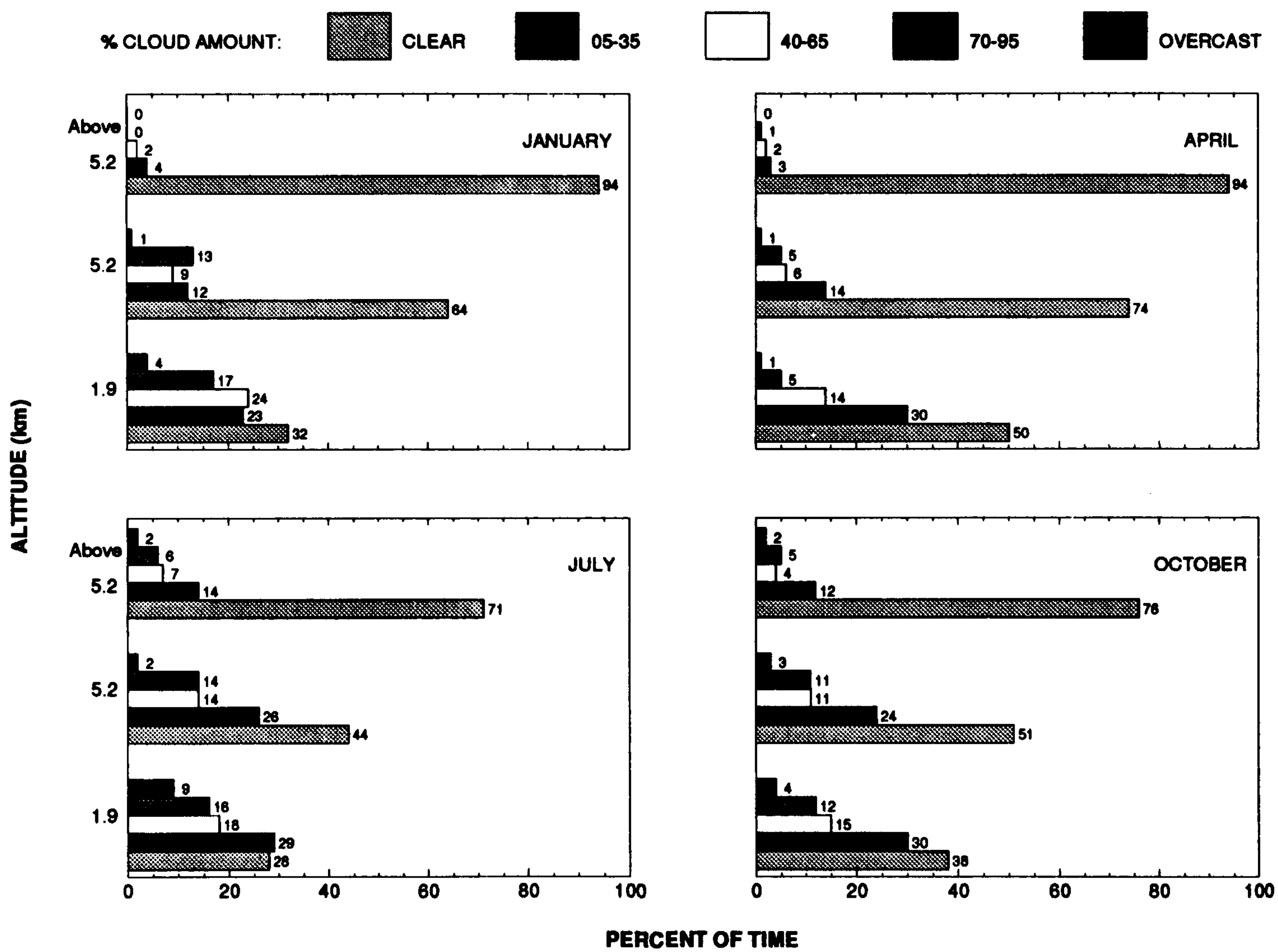
(20.0°N, 155.0°E)



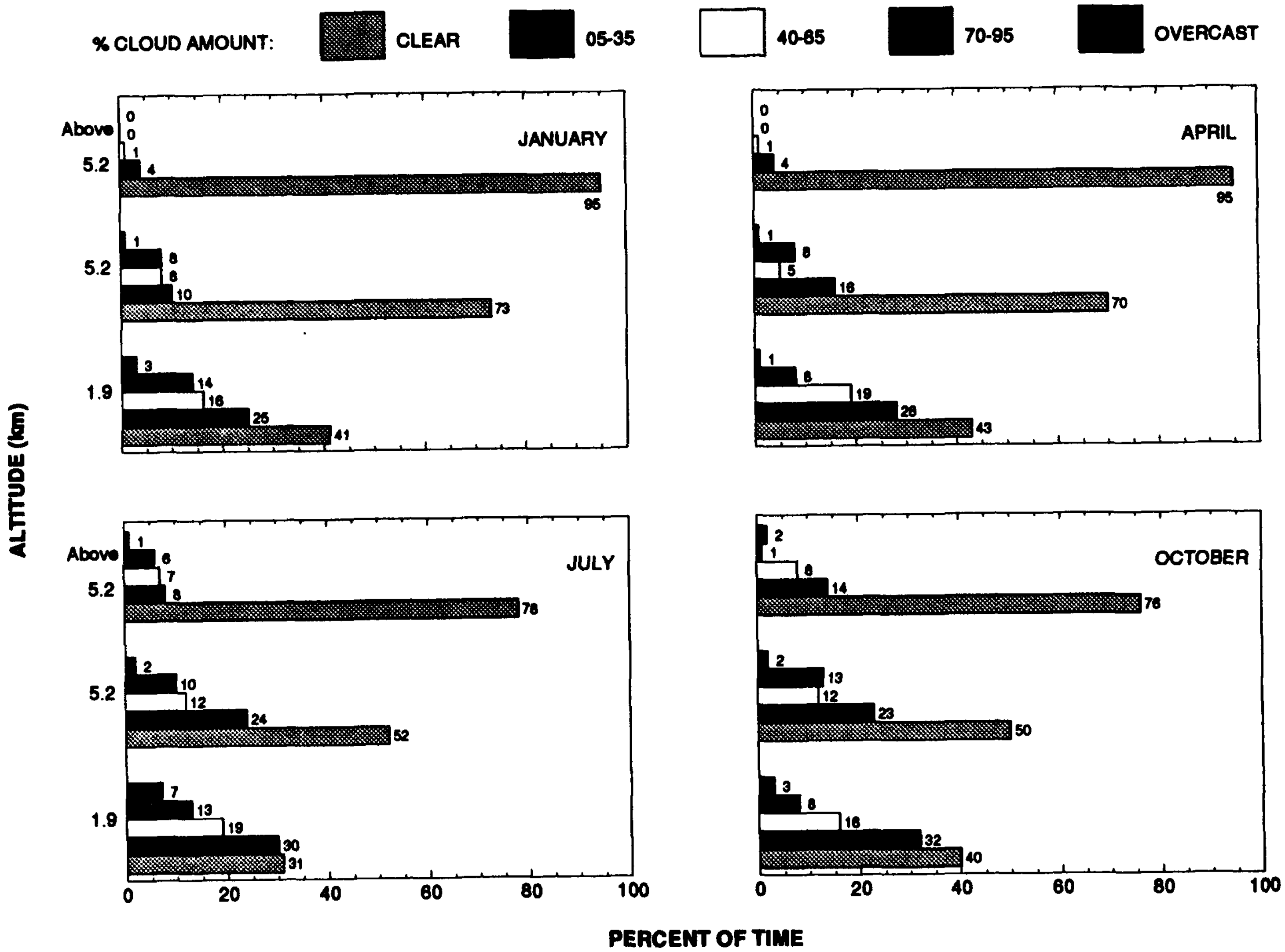
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(20.0°N, 160.0°E)



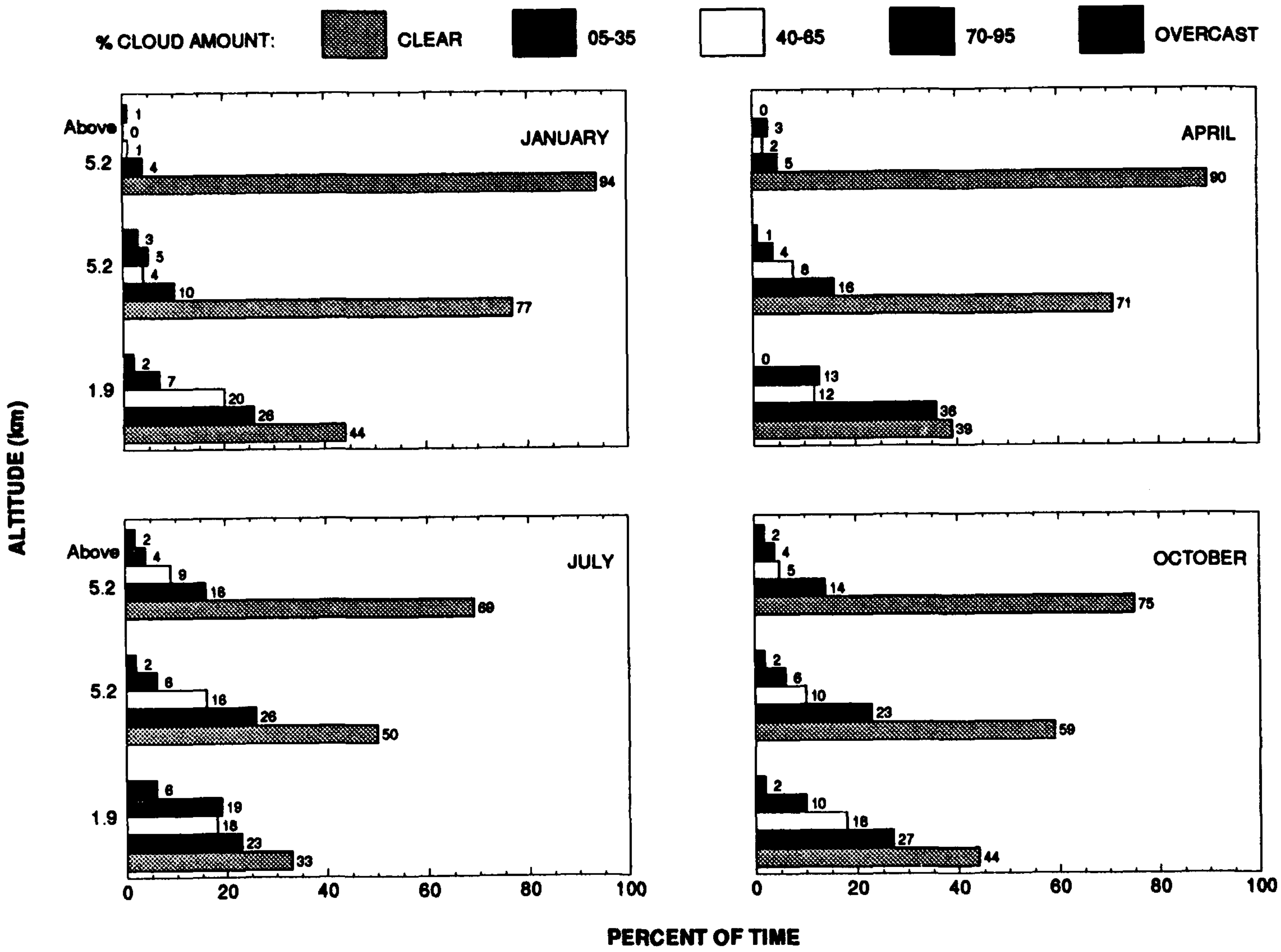
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(20.0°N, 165.0°E)



CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(20.0°N, 170.0°E)



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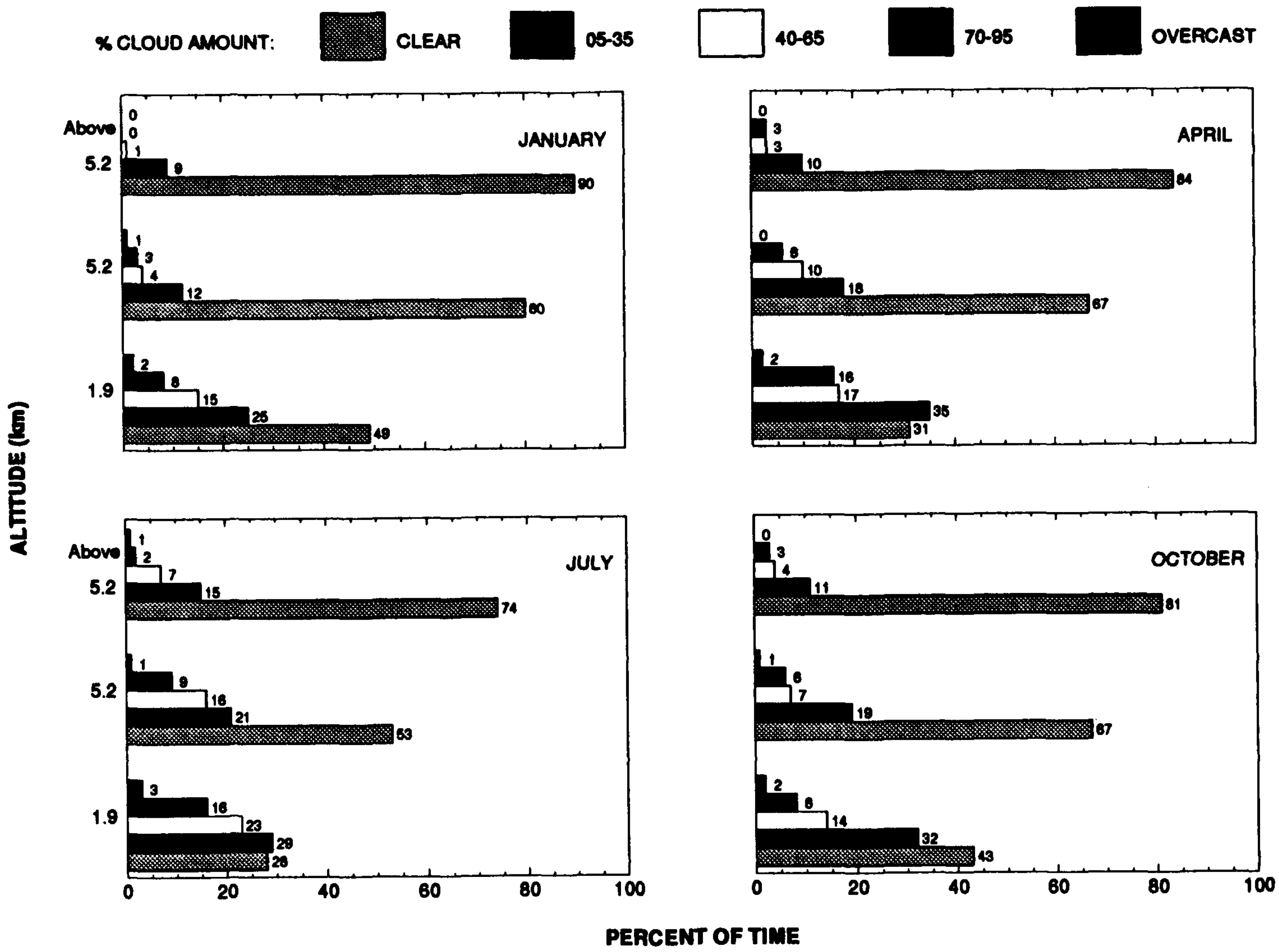
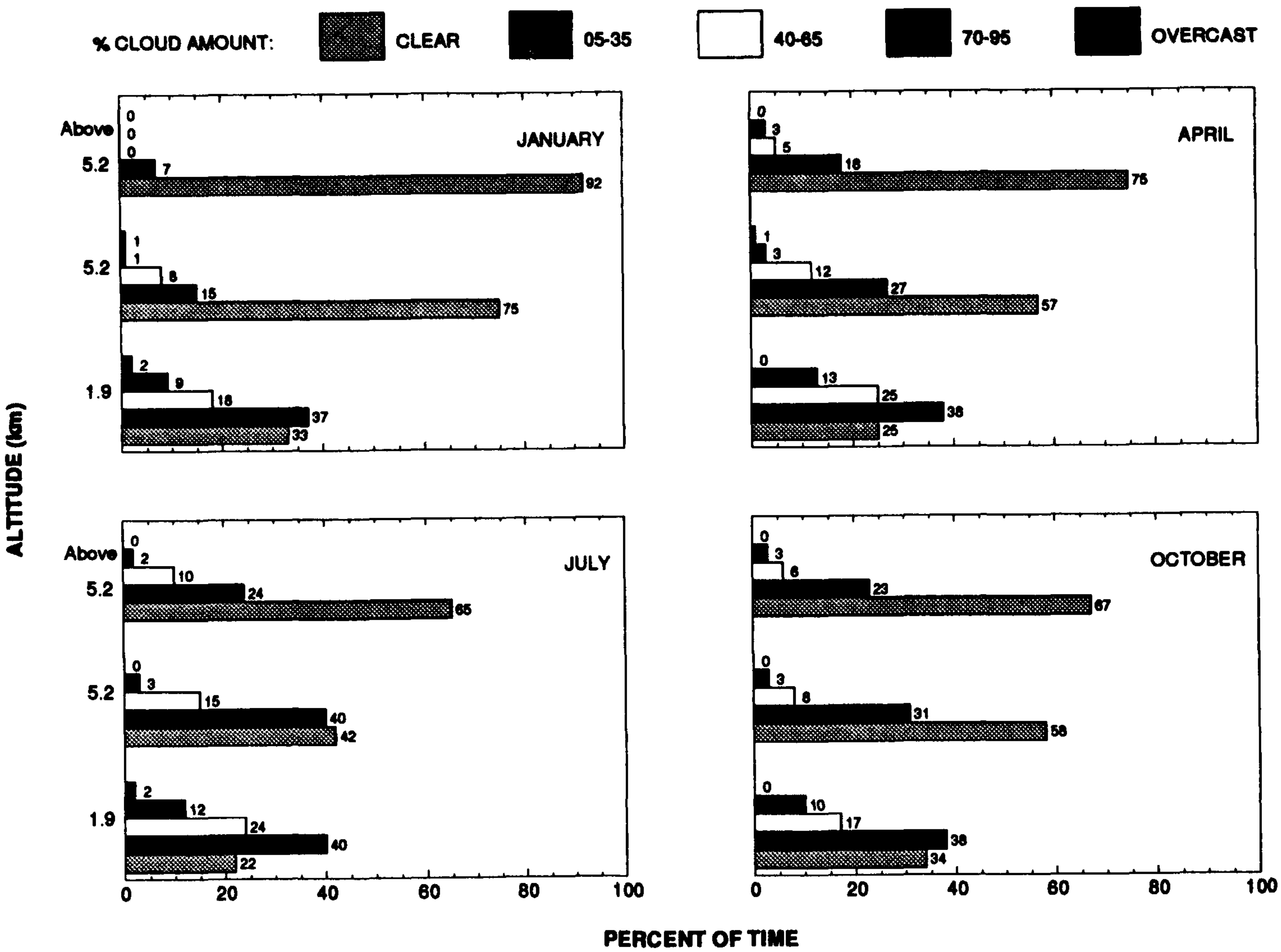
(20.0°N, 175.0°E)



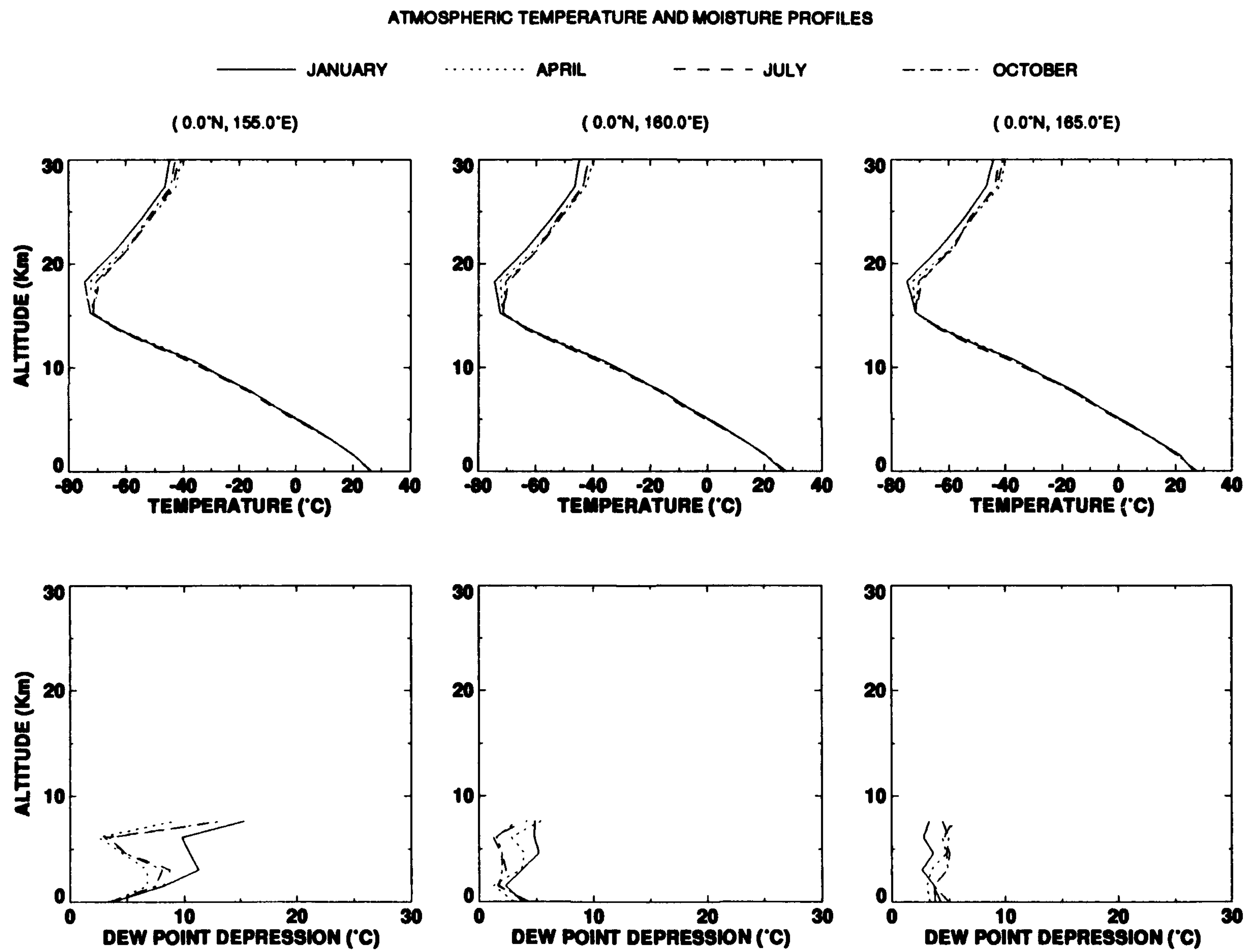
CLOUD AMOUNT FREQUENCY OF OCCURRENCE FOR LOW, MIDDLE, AND HIGH CLOUDS

(20.0°N, 180.0°E)



APPENDIX C

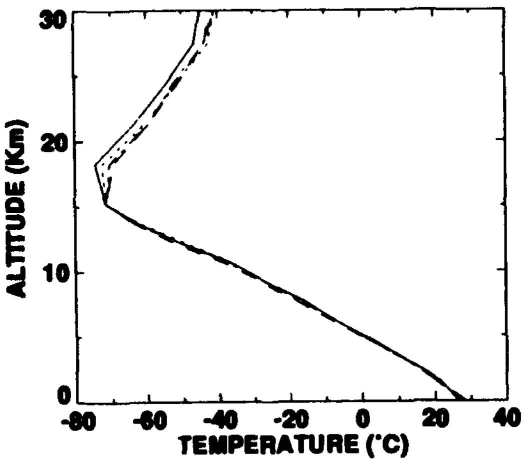
ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES

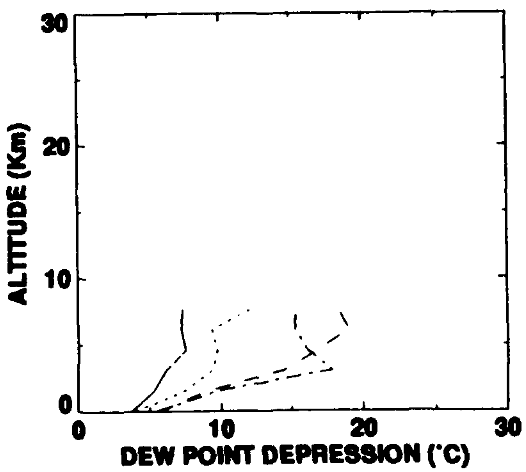

ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES
JANUARY
APRIL
JULY
OCTOBER
(0.0°N, 155.0°E)
(0.0°N, 160.0°E)
(0.0°N, 165.0°E)
ALTITUDE (Km)
TEMPERATURE (°C)
DEW POINT DEPRESSION (°C)
30
20
10
0
-80
-60
-40
-20
0
20
40
0
10
20
30

ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES

JANUARY ········· APRIL — — — JULY —·—·— OCTOBER

(0.0°N, 170.0°E)





(0.0°N, 175.0°E)

Missing

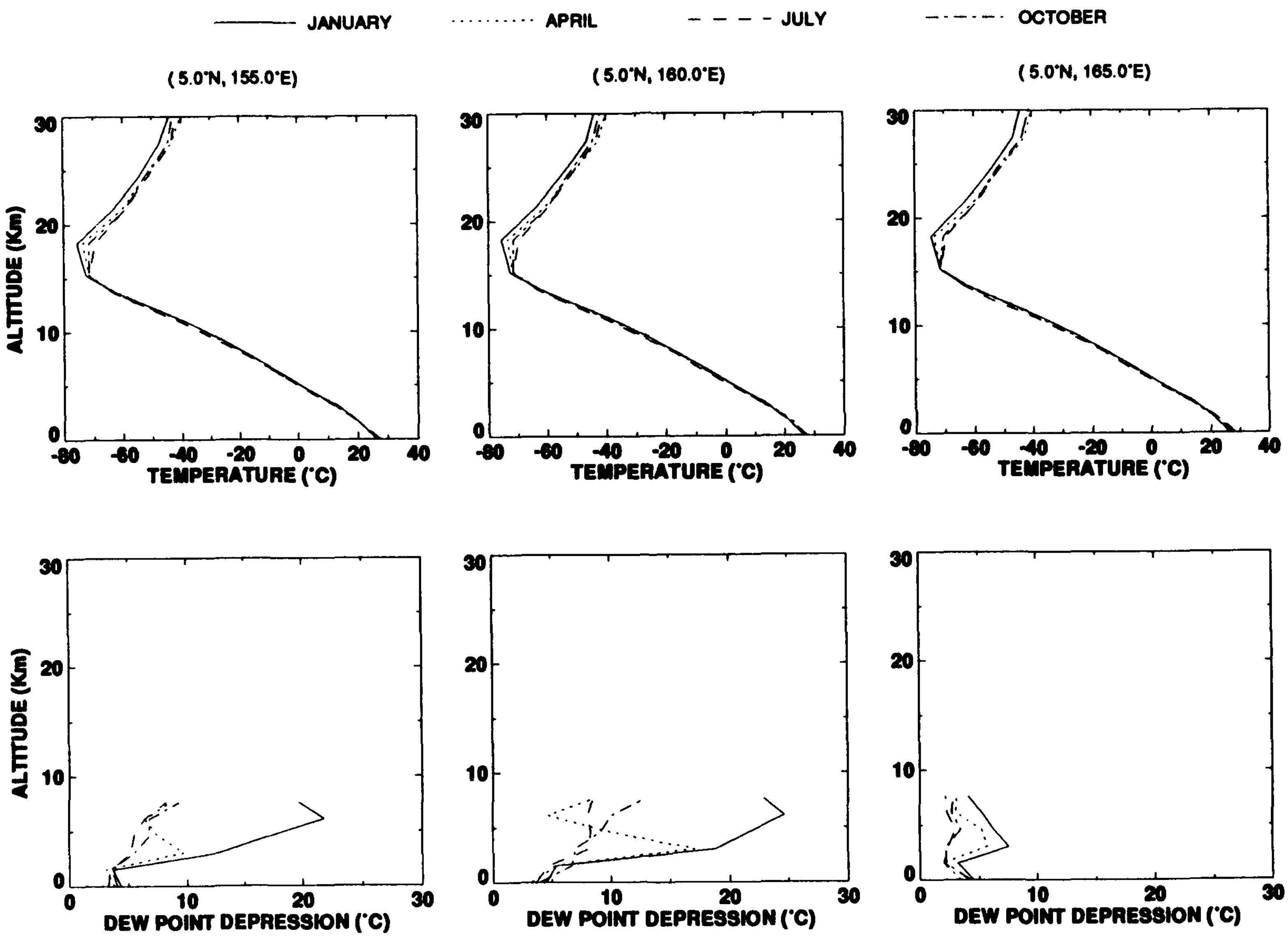
Data Points

(0.0°N, 180.0°E)

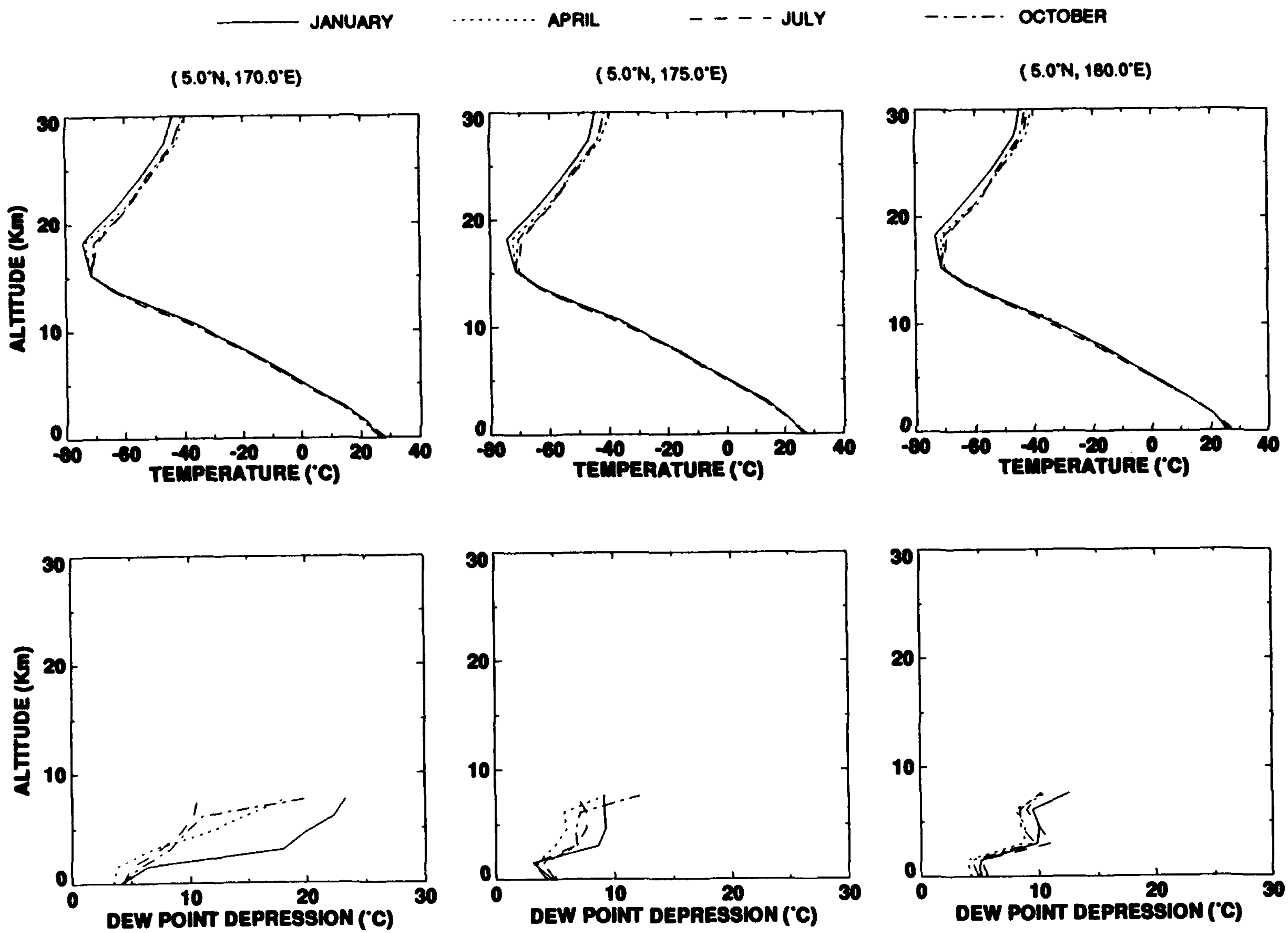
Missing

Data Points

ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES



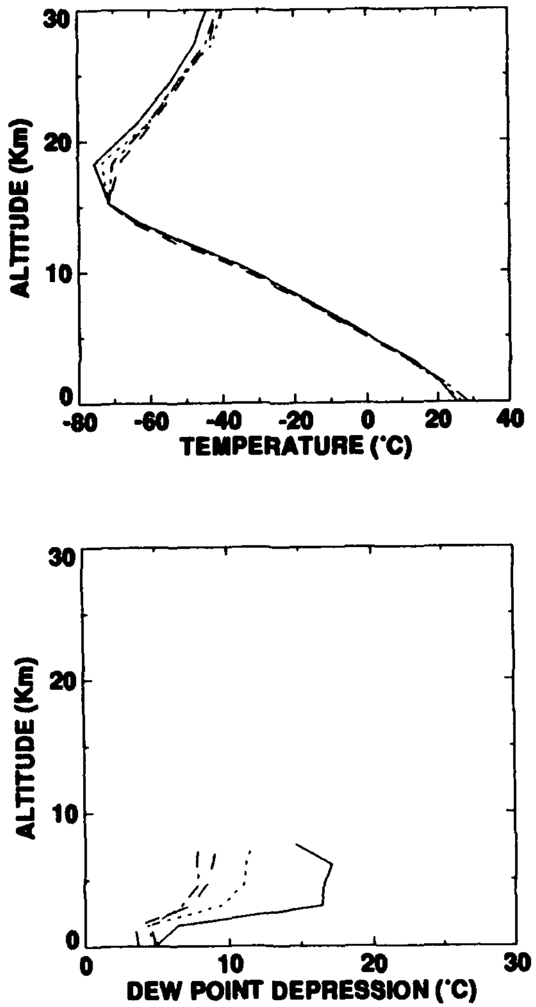
ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES



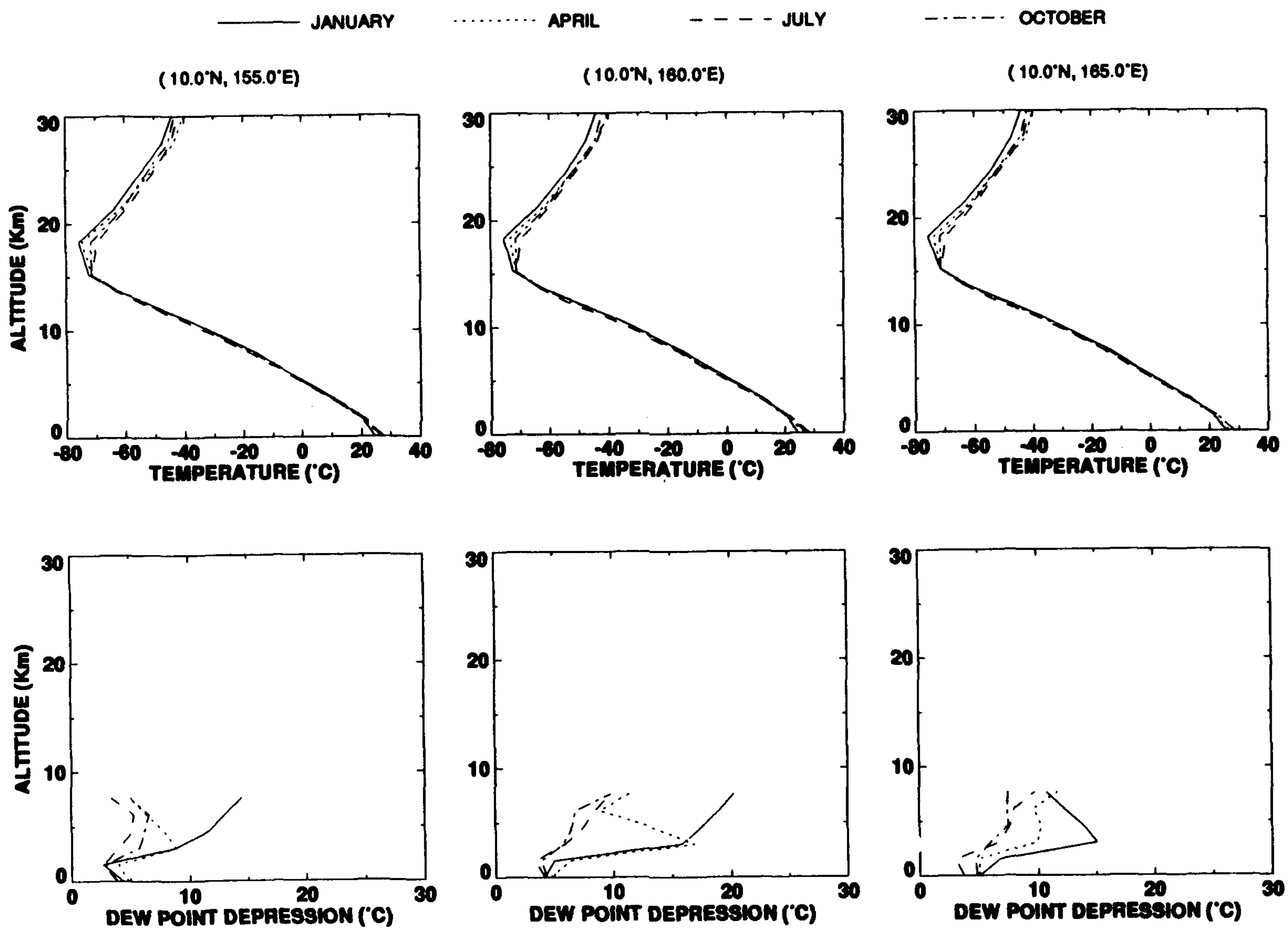
ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES

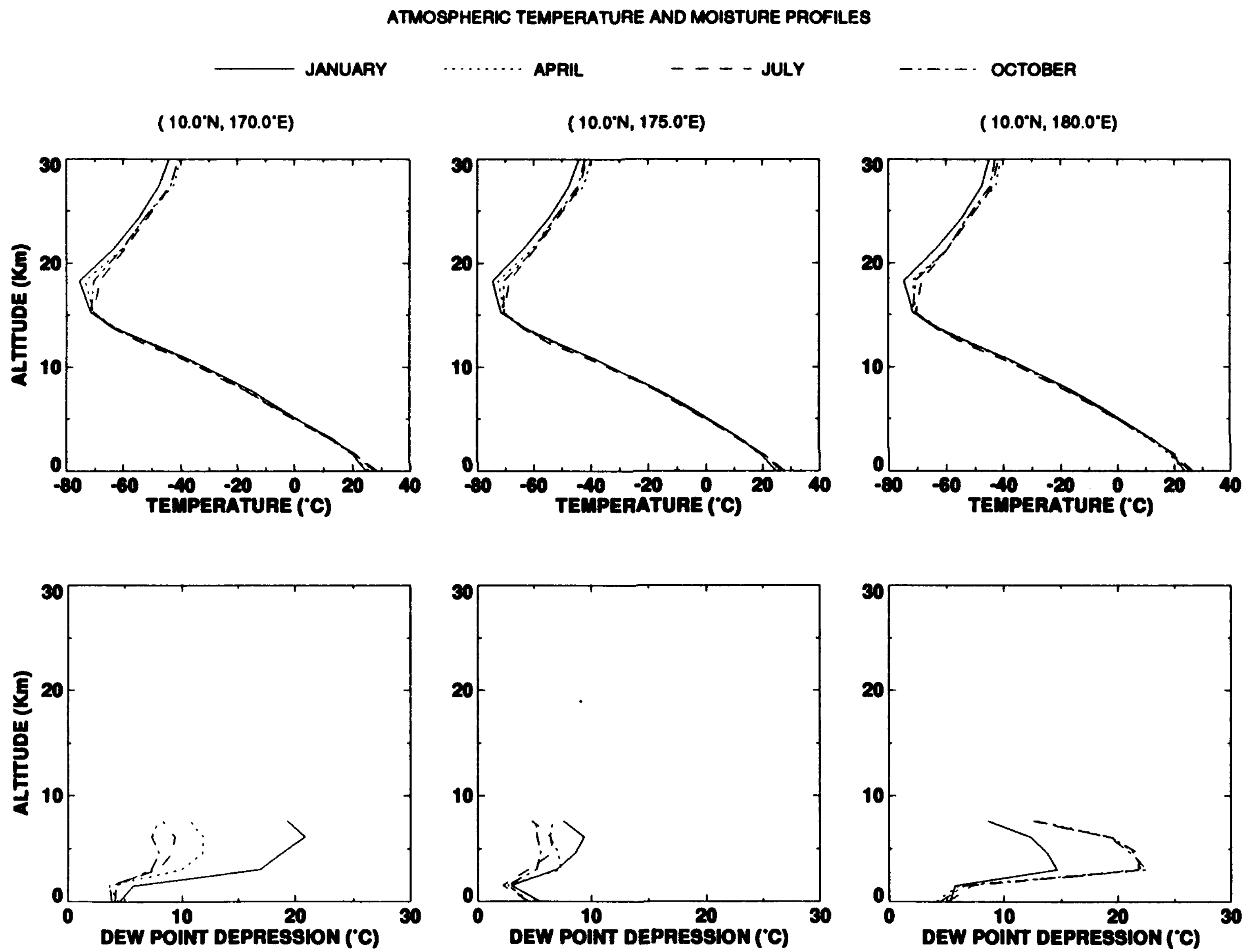
——— JANUARY ········· APRIL – – – – JULY –·–·–· OCTOBER

KWAJALEIN (9.4°N, 167.5°E)

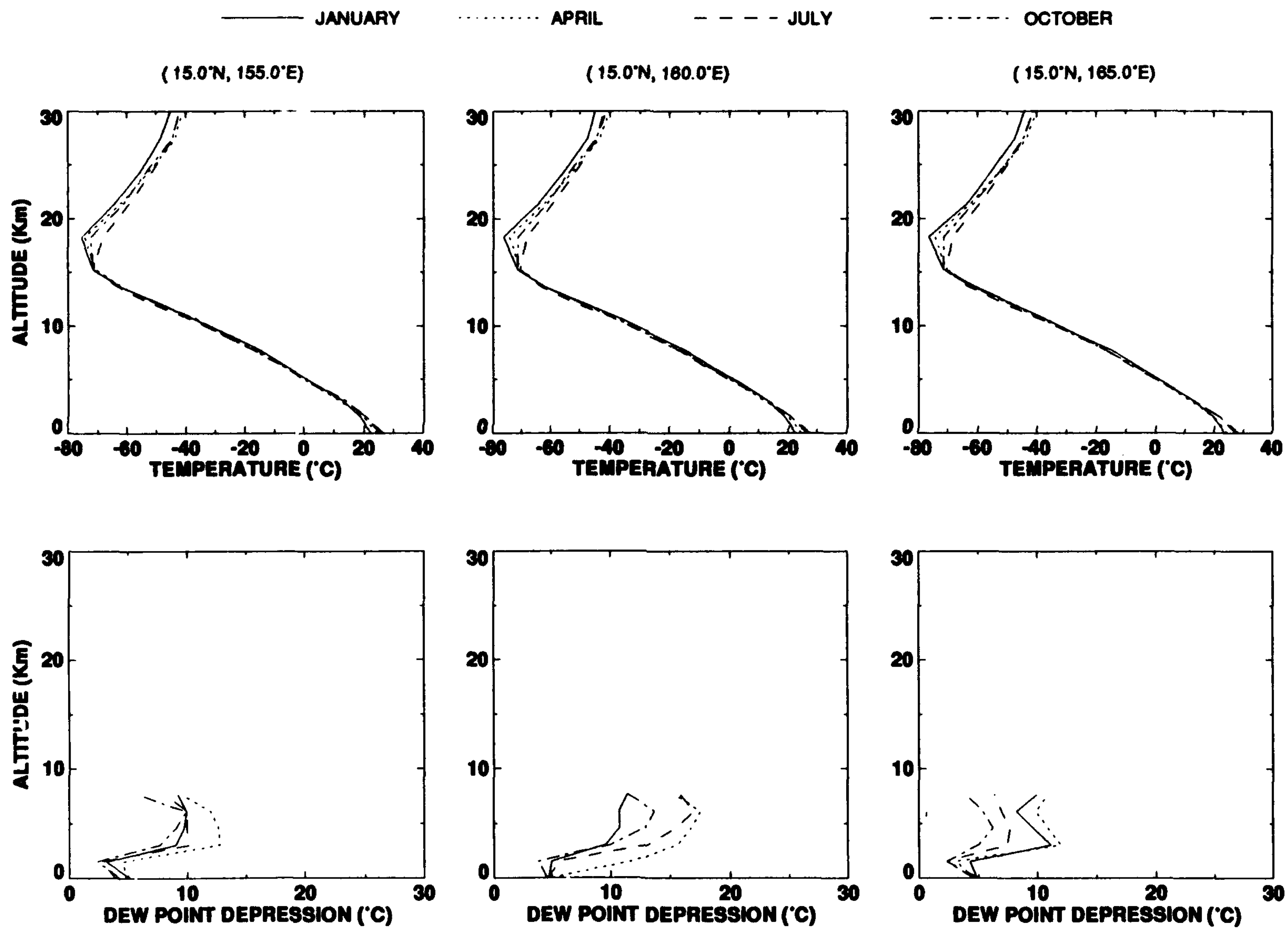


ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES

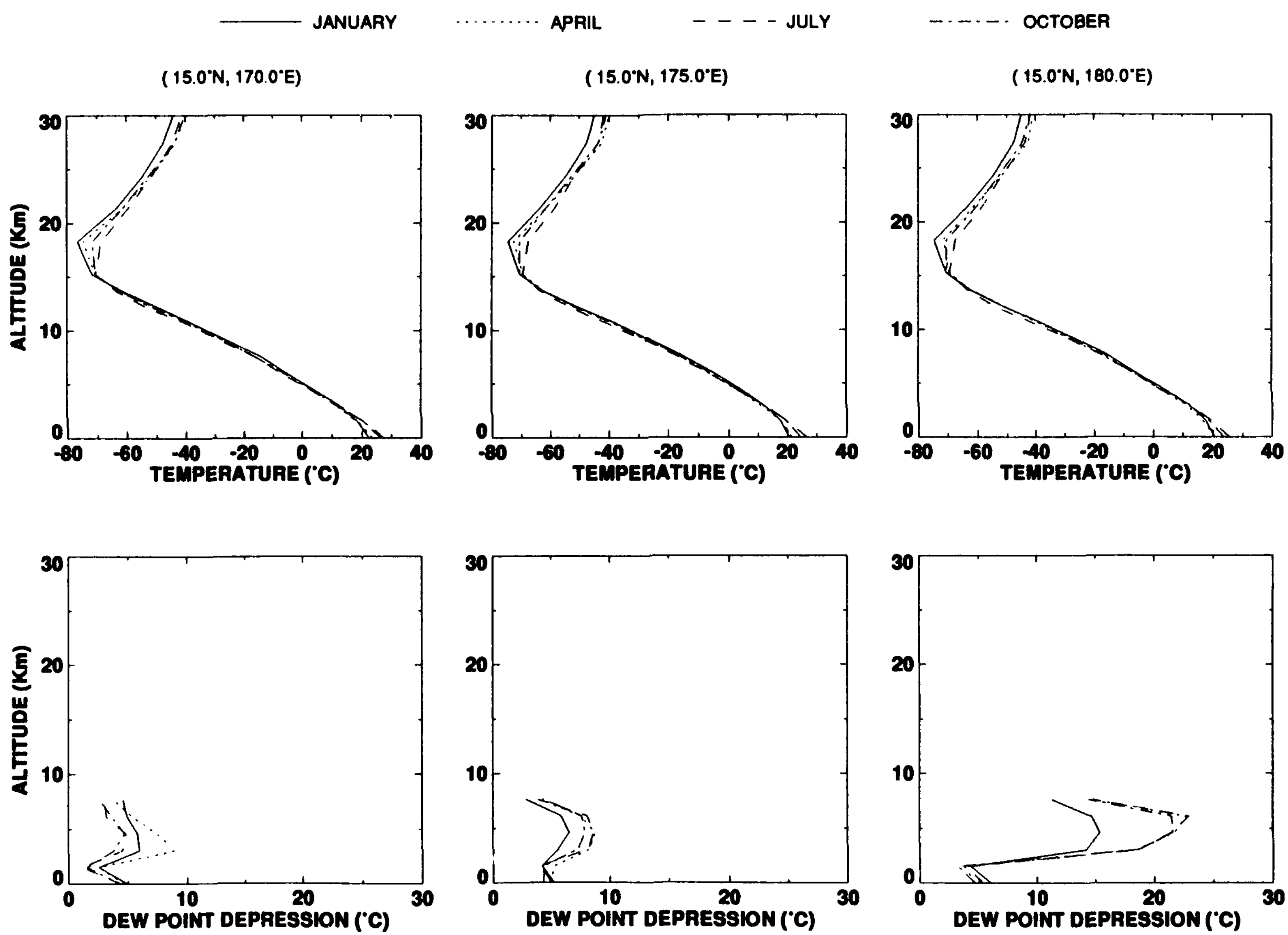


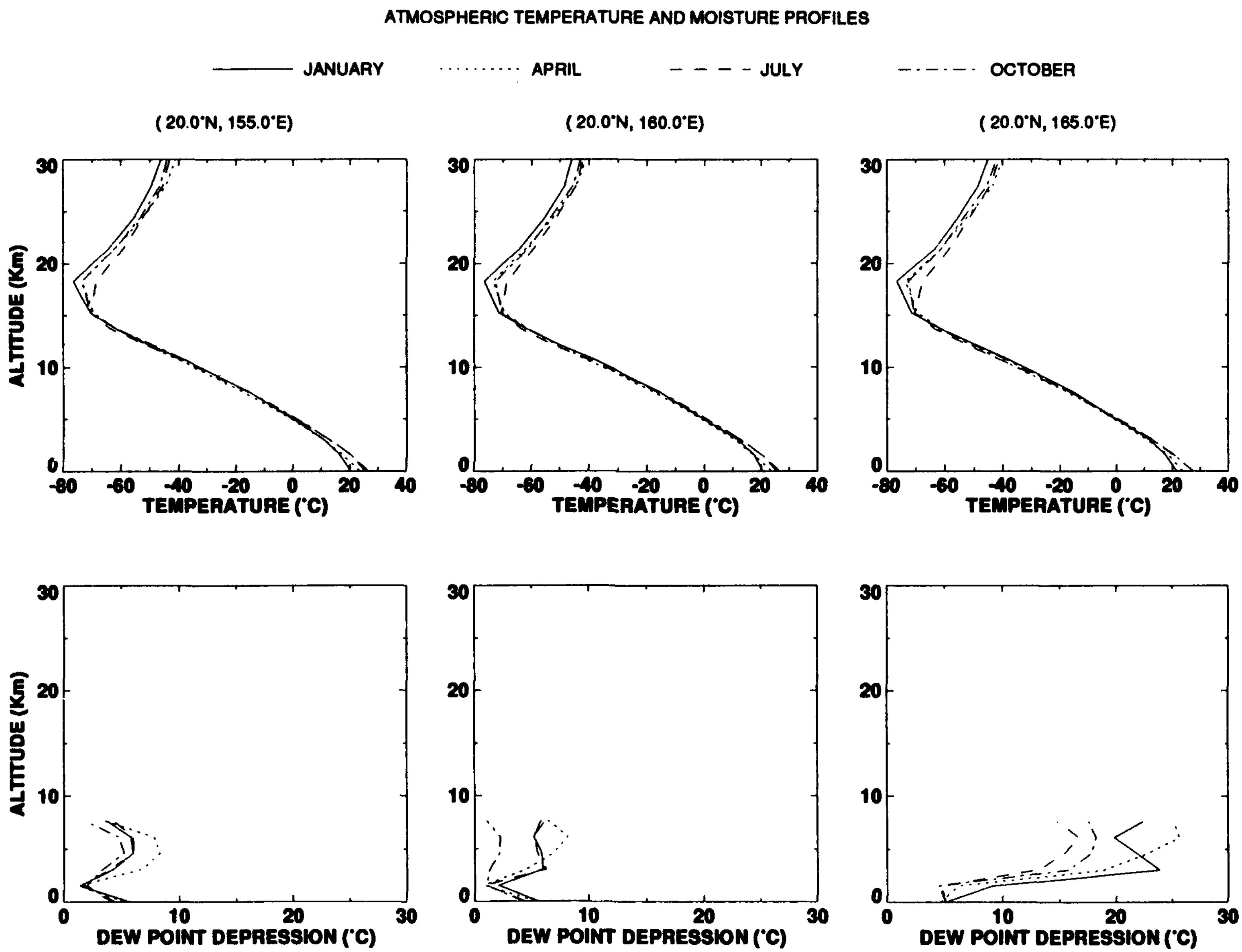

ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES
JANUARY
APRIL
JULY
OCTOBER
(10.0°N, 170.0°E)
(10.0°N, 175.0°E)
(10.0°N, 180.0°E)
ALTITUDE (Km)
TEMPERATURE (°C)
DEW POINT DEPRESSION (°C)
30
20
10
0
-80
-60
-40
-20
0
20
40
0
10
20
30

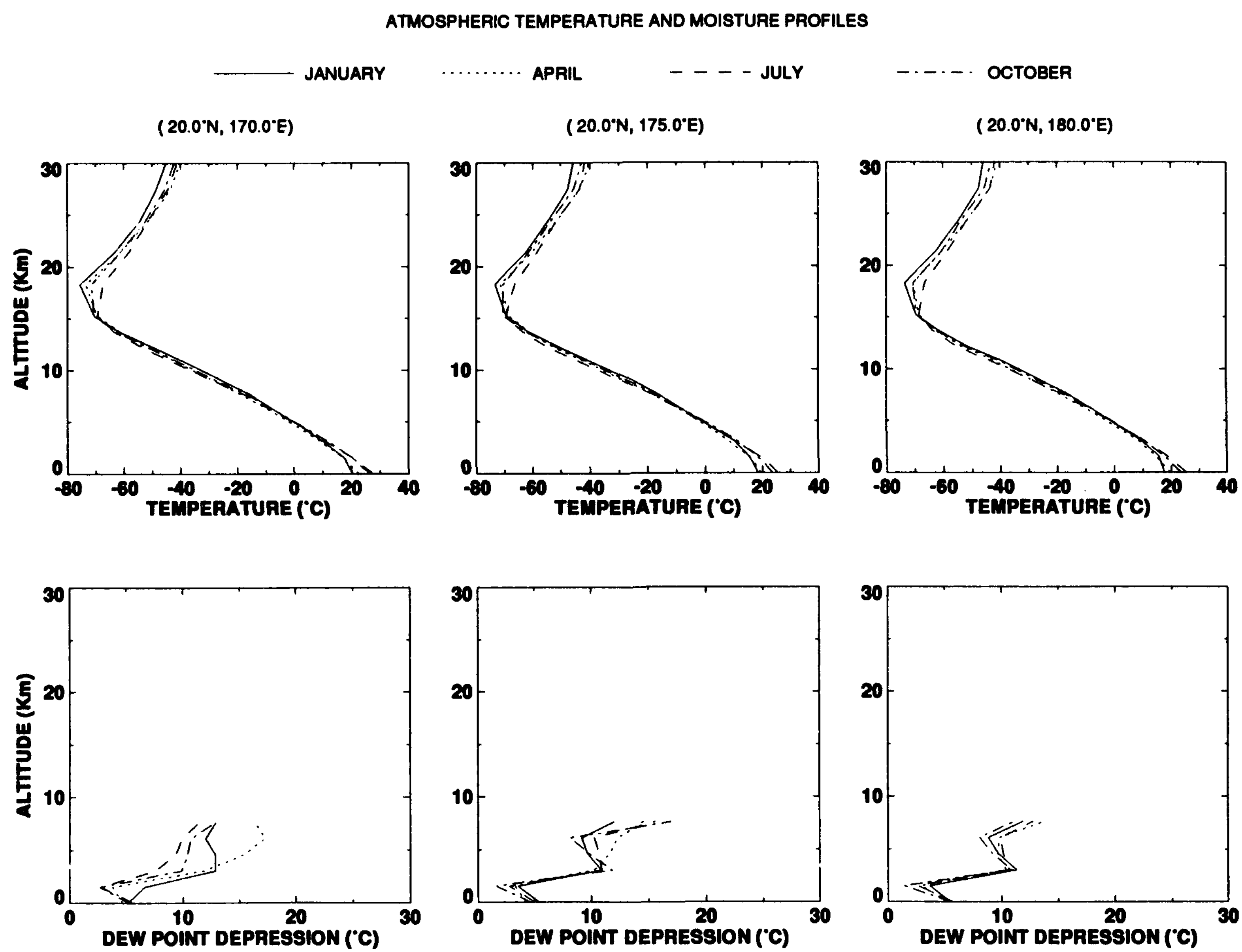
ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES



ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES




ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES
JANUARY
APRIL
JULY
OCTOBER
(20.0°N, 155.0°E)
(20.0°N, 160.0°E)
(20.0°N, 165.0°E)
ALTITUDE (Km)
TEMPERATURE (°C)
DEW POINT DEPRESSION (°C)
-80 -60 -40 -20 0 20 40
0 10 20 30


ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES
JANUARY
APRIL
JULY
OCTOBER
(20.0°N, 170.0°E)
(20.0°N, 175.0°E)
(20.0°N, 180.0°E)
ALTITUDE (Km)
TEMPERATURE (°C)
DEW POINT DEPRESSION (°C)

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13. ABSTRACT (*Maximum 200 words*)

A cloud climatology for the Kwajalein area in the tropical Pacific presents cloud statistics for Kwajalein (9.4°N, 167.5°E) and 30 locations within approximately 1000 km of Kwajalein. The statistics are derived from a five-year sample (1977 – 1983) of the Air Force 3D-Nephanalysis Global Cloud Archive (known as the 3D-NEPH model). Mean cloud amount and cloud amount frequencies of occurrence are presented for four representative months for three cloud layers: low (surface to 1.9 km), middle (1.9 to 5.2 km), and high (>5.2 km). Cloud-top heights and temperatures are also estimated from atmospheric profile data. The cloud climatology presented in this report updates previous climatologies and presents cloud statistics for Kwajalein and the surrounding area in a format usable for determining LWIR upwelling earthshine.

14. SUBJECT TERMS
3D-Nephanalysis — Kwajalein meteorology
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